LAND MANAGEMENT HANDBOOK

53

Estimating Historical Variability of Natural Disturbances in British Columbia

2003

BRITISH COLUMBIA
Ministry of Forests
Forest Science Program
Ministry of Sustainable Resource Management
Resource Planning Branch

104-05891/

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National Library of Canada Cataloguing in Publication Data

Wong, Carmen, 1973-
Estimating historical variability of natural disturbances in British Columbia

(Land management handbook ; 53)

Co-published by Ministry of Sustainable Resource Management, Resource Planning Branch.
Includes bibliographical references: p.
ISBN 0-7726-5060-8

1. Ecological disturbances - British Columbia - History. 2. Forests and forestry - Environmental aspects - British Columbia. 3. Reforestation - British Columbia. 4. Forest regeneration -- British Columbia. 5. Forest management - British Columbia. I. Dorner, Brigitte, 1967-. II. Sandmann, Holger. III. British Columbia. Forest Science Program. IV. British Columbia. Ministry of Sustainable Resource Management. Resource Planning Branch. V. Title. VI. Series.

SD418.3.C3W66 2003 634.961'09711 C2003-960216-8

Citation

Wong, C., B. Dorner, and H. Sandmann. Estimating historical variability of natural disturbances in British Columbia. B.C. Min. For., Res. Br., B.C. Min. Sustain. Resource. Manage., Resource Plan. Br., Victoria, B.C. Land Manage. Handb. No. 53.

www.for.gov.bc.ca/hfd/pubs/Docs/Lmh/Lmh53.htm

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Co-published by

B.C. Ministry of Forests
Forest Science Program
PO Box 9519 Stn Prov Govt
Victoria, BC V8W 9C2
and
B.C. Ministry of Sustainable Resource Management
Resource Planning Branch
PO Box 9373 Stn Prov Govt
Victoria, BC V8W 9M3

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Victoria, BC V8W 1E7
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EXECUTIVE SUMMARY

Natural disturbances are an integral part of the processes shaping and maintaining the forested landscapes in British Columbia. Understanding the historic variability in the frequency, intensity/severity, size, and duration of natural disturbances is important for guiding sustainable forest management and projecting the effects of natural disturbances on habitat and timber supply. This report is composed of four parts: the first three are stand-alone reports, whereas the fourth and final part makes recommendations based on the results of the first three parts.

Part 1 presents a concise review of natural disturbance dynamics for each of the 14 biogeoclimatic zones in British Columbia. We reviewed published and unpublished research specific to British Columbia and in similar ecosystems outside British Columbia. We identified significant gaps in the geographic coverage of research; the temporal depth of research; research on disturbance agents other than fire; and interactions between disturbances, climate change, and human activities. Attributes of disturbances other than frequency are also poorly described in British Columbia—only one-quarter of subzones have descriptions of the historical distribution of the size of disturbance patches.

Part 2 presents 11 methods described in the literature for determining intervals for stand-replacing and stand-maintaining disturbances. Methods are organized into groups based on the type of data source required. For each method we describe the principle on which the method is based, its strengths and weaknesses, and the type of data and assumptions required. A step-by-step guideline identifies one or more appropriate methods to select, prepare, use, and analyze available data with a focus on data available to timber supply reviews in British Columbia (e.g., Forest Inventory Planning data). Decisions at each step are based on (1) the type of the disturbance regime encountered in the study landscape; (2) the type(s) of data available; and (3) the expected characteristics of the disturbance regime.

Part 3 demonstrates an application of the process outlined in Part 2 for selecting and using one of the methods for determining disturbance intervals in the Arrow Forest District. Primarily, we wanted to show the potential of using Forest Inventory Planning (FIP) data for disturbance analysis, with attention to the various sources of uncertainty researchers are likely to encounter, such as data accuracy, historical disturbance dynamics, and historical harvesting activities. This uncertainty was represented by incorporating a stochastic model of error in FIP age and by considering six different scenarios representing alternative assumptions about historical disturbance dynamics.

The Rollback Method, where the standing age distribution is "rolled back" in time by successively reassigning disturbed forest (younger age classes) to older age classes, was used to reconstruct changes in disturbance return intervals between 1700 and 2000 in seven variants of the Interior Cedar–Hemlock and Engelmann Spruce–Subalpine Fir biogeoclimatic zones. Disturbance return intervals of stand-replacing disturbances were highly variable over the past 300 years. Although a decrease in disturbance rates during the later part of the 20th century was evident in many of the variants, the size of decrease was well within the range of historical variability in disturbance rates for most scenarios. Our results provided no clear support for the hypothesis that fire suppression has been effective in the Arrow Forest District. Consequently, larger disturbance episodes in the future, which could prove to be difficult to suppress, may recur. Also, when determining harvest rates and setting landscape objectives for late-seral forest and old forest connectivity, allowances need to be considered for losses to natural disturbance.

The uncertainty in reconstructed return intervals increased the further we went back in time. Uncertainty in FIP age estimates, in the pre-harvest age of logged areas, and about the relative importance of large episodic, small, or stand age–dependent disturbances were highly influential. The random component of scatter in FIP age around true age substantially influenced the results because it obscured potentially meaningful peaks in the true age distribution and made it difficult to associate fluctuations in disturbance rates with potential driving factors such as human activities or climate. The results from reconstructions based on standing age distributions are sensitive to the assumptions in the analysis about these sources of uncertainty. To avoid biased conclusions, studies need to represent the full range of uncertainty about historical disturbance dynamics.

We observed a large amount of variability in historic landscape dynamics. This suggests that managing for objectives such as seral stage distributions should be based on the range of historical variability rather than steady-state (single value) targets.

Part 4 presents our recommendations to address the gaps we identified in research on disturbance dynamics, data collection, and data maintenance, as well as quantitative methods for determining disturbance intervals in British Columbia. We conclude with recommendations from our work for incorporating knowledge of natural disturbances into forest planning and management.

ACKNOWLEDGEMENTS

This report, particularly Part 1, involved requesting disturbance information and reports from many people in British Columbia, Alberta, and the United States. We thank the following for making information available to us: Abitibi Consolidated, Greg Anderson, Dave Andison, Andre Arsenault, Geraldine Bergmans-Jordan, Tom Braumandl, Derek Bronin, Steve Cumming, Dan Gavin, Don Gayton, Bob Gray, Doug Hallet, Brad Hawkes, Mark Heathcott, Peter Impala, Walt Klenner, Lignum Ltd., Eliot McIntire, Don Morgan, Chris Opio, Roberta Parish, John Parminter, Audrey Pearson, Murray Peterson, John Pollack, Harry Quesnel, Marie-Pierre Rogeau, and Don Steventon.

We appreciate the thorough review of this report by Joseph Fall. We also incorporated useful comments from John Parminter, Dave Conly and Tory Stevens. In particular, we thank Marvin Eng and Andy MacKinnon for their thoughtful feedback and support along the way.

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1 LITERATURE REVIEW OF CURRENT KNOWLEDGE

Carmen Wong, Holger Sandmann, and Brigitte Dorner

1.1 Introduction

Natural disturbances drive patterns in forest structure at various temporal and spatial scales (Turner et al. 1993; Lertzman et al. 1998; Swetnam and Betancourt 1998). Because one of the goals of current forest management is to model management actions on the temporal and spatial dynamics of natural processes (e.g., the *Biodiversity Guidebook;* [B.C. Ministry of Forests and BC Environment 1995]), knowledge about the historic variability of natural disturbances is an important prerequisite. No comprehensive summary or review of research on natural disturbances in the various forested ecosystems across British Columbia has been published. The authors of the *Biodiversity Guidebook* used expert opinion to broadly classify biogeoclimatic subzones into five natural disturbance types (NDTs); however, the guidebook does not list any of its sources. Furthermore, NDTs are based on disturbance return interval and resulting patch size distribution of wildfires and incorporate only limited information on disturbance agents other than fire.

This part of our report provides baseline information for each biogeoclimatic zone (and its subzones and variants) on what is known about the historical patterns and dynamics of natural disturbances. It gives an overview and a comprehensive literature database for anyone interested in the historic variability of natural disturbances throughout the province. We summarize important disturbance agents and studies about them by biogeoclimatic *zone* in the text and list all available estimates of disturbance attributes by biogeoclimatic *variant* in Table 1. We used the units of biogeoclimatic zones and subzones/variants to summarize information; however, we realize that for some disturbance agents, such as geomorphic disturbances, a physiographic unit is more appropriate. We also point out the gaps in knowledge, both within the text and—as obvious empty rows—in the Table. Note that Parts 2–4 of our report provide tools, examples, and recommendations on how to fill these gaps.

While this review discusses the development of natural resource management guidelines that use the concept of range of natural variability, the information presented here is insufficient, on its own, to replace any existing guidelines.

1.2 Sources of Information

We used many different sources of information, including peer-reviewed journal articles, theses, published and unpublished reports, and databases. We summarized research in each biogeoclimatic zone within three categories: (1) field-based studies from British Columbia specific to the zone; (2) field-based studies from similar ecosystems (United States, Alberta, others); and (3) simulation modelling of natural disturbances in the zone. Where possible, we focused on research conducted in British Columbia and used the organizational structure of the B.C. Ministry of Forests prior to April 2003 to refer to general locations. However, because British Columbia–based research remains limited for several biogeoclimatic zones, we also reviewed research published about similar ecosystems in the United States and Alberta. Even though our review is based on more than 280 references, we likely missed a few completed studies in addition to ongoing projects. Therefore, we consider this review incomplete and encourage its distributors and users to add new information as it becomes available.

1.3 Interpretation of Information

For each biogeoclimatic zone, we summarized information on stand-replacing and stand-maintaining disturbance agents. For each agent, we listed attributes of frequency, extent, spatial distribution, and severity. Much of what we present here is a function of available research and what is reported in each study. We report values as they were reported. Therefore, measures of disturbance attributes are not always consistent (see inset box). This presents challenges for comparing information both within and among different biogeoclimatic subzones. However, converting values to common measures would have required obtaining raw data from the authors and/or careful re-analysis, which was beyond the scope of this project.

A Note of Caution We *strongly* caution readers to avoid uncritically comparing the information summarized in this review, particularly the disturbance intervals reported in Table 1. The measures of disturbance frequency reported in the source documents are usually specific to a certain location, sample size, size of study area, time period, and method. For example, mean fire intervals determined from charcoal accumulation in lake sediments typically have much greater temporal depth than the studies based on tree data but they lack the temporal resolution and spatial control of the latter. Mean fire intervals determined from fire scars, sampled from trees in plots over an area, give fire intervals for the study area if scars from all the plots are pooled for the extent of the temporal record; consequently, the fire interval given depends on the size of the study area. Analysts often censor the temporal record to a "period of reliability" (e.g., Grissino-Mayer 1995) during which the sample size was large enough to ensure confidence in fire dates. Fire cycles or disturbance rates determined from time-since-fire maps (i.e., using stand-origin maps as proxies) supply a measure of disturbance frequency that is independent of study area size but the results are limited to stand-replacing disturbances only. Studies based on time-since-fire maps are also limited in temporal depth to the lifespan of the post-fire cohorts and are often conducted over much larger areas than studies based on the analysis of fire scars.

1.4 Literature Review: Disturbance Attributes by Biogeoclimatic Zone

The 14 biogeoclimatic zones in British Columbia differ in the numbers and types of disturbance agents active in the zone. These differences are primarily due to host specificity of biotic disturbance agents. For example, eastern spruce budworm defoliates subalpine fir, white spruce, and Engelmann spruce in only the boreal forests of northeastern British Columbia, whereas western blackheaded budworm defoliates primarily western hemlock and true firs in the coastal biogeoclimatic zones and a few of the wetter interior zones (B.C. Ministry of Forests 1995). Those disturbance agents that are not host-specific, such as most abiotic disturbances, tend to occur in every biogeoclimatic zone, but due to differences in climate and topography occur more frequently and over more area in some zones than others. For example, avalanches rarely occur in the Interior Douglas-fir zone because this zone receives insufficient snow but occur frequently in the subalpine zones because of the snow load and steep topography (Wong 2001).

Biogeoclimatic zones also differ in how frequently and with what intensity each disturbance agent occurs in the zone. Most diseases occur at endemic levels, most insects occur at both endemic and outbreak levels at some return interval, and most abiotic disturbances occur at variable to regular return intervals (Wong 2001).

Measures of Disturbance Frequency

Fire cycle is often used interchangeably with **mean return interval** and sometimes also with **mean fire interval**. Fire cycle is the time to burn an area equivalent to the studied landscape (in this time, fires may burn some areas more than once and others not at all) and is always independent of the size of the study area. It is typically used in studies that estimate the frequency of high-severity fires from age structure across a landscape. Mean fire interval (MFI) is sometimes defined as the average expected time between fires at a given point in the landscape (mean point interval), but is more commonly used to describe the expected average time between fires occurring *anywhere in the study area*. MFI thus often depends on the size of the study area and is therefore difficult to transfer to areas of a different size, unless the distribution of fire sizes is known (Baker and Ehle 2001). MFI is typically used for studies based on charcoal deposition in lake sediments or for studies of stand-maintaining and mixed-severity regimes based on fire scars. The fire cycle equals the mean (point) fire interval if fires start at random locations and burn equally across all areas of a landscape.

The fire cycle is also the inverse of the **annual disturbance rate**, the annual proportion of the landscape disturbed. Thus, if the fire cycle equals the mean fire interval, a (point) fire interval of 100 years means that an average of 1% of the study area will be disturbed each year and an average time of 100 years will elapse between fires at any point in the landscape.

Given the many biogeoclimatic subzones and variants, it would have been difficult and confusing to systematically review each variant. Instead, we used the level of biogeoclimatic zone to organize information in this written part of the review. However, we do indicate the variant where studies have listed them. We use variants instead of subzones because variants are often geographically distinct and therefore might contain different disturbance types and dynamics.

If you are planning to use any of the results of the studies summarized below, please refer to the original study. Many of the methods and datasets involved specific assumptions and manipulations, which often differ between studies, and are not given here.

Alpine Tundra Zone

The Alpine Tundra zone (AT) occupies high mountain areas throughout British Columbia and occurs above the three subalpine zones: MH, ESSF, and SWB. Its lower elevational boundary ranges from ~1000 m in northwest British Columbia to ~2250 m in the southeast (Pojar and Stewart 1991a). The AT has the harshest climate of any of the BEC zones in British Columbia, with much wind and snow and very short frost-free periods. Mean annual precipitation is estimated to range from 700 to 3000 mm, most of which (70–80%) falls as snow (Pojar and Stewart 1991a).

Pojar and Stewart (1991a) list three major divisions of the AT—maritime or coastal, northern interior (north of 56° latitude), and southern interior—but no formal separations into subzones have been agreed upon to date. Douglas and Bliss (1977) are an additional source for data on ecological differences between coastal and southern interior community types.

The interactions of wind, snow, and topography result in a mosaic of grasslands, dwarf-shrublands (alpine heaths), and patches of bare soil or rock. While the lower boundary of the AT generally coincides with the upper treeline, widely scattered individuals or islands of trees occupy sheltered sites. Typically, these conifers grow in stunted or krummholz form, their height largely determined by the depth of the snowpack (Douglas and Bliss 1977).

Most disturbances agents are directly associated with the harsh climate and local relief. Abiotic disturbances include wind and frost damage, snowcreep, avalanches, and fire (Brink 1964). Main biotic agents of disturbance are defoliators, such as western hemlock looper and 2-year-cycle spruce budworm; white pine blister rust; as well as native or introduced ungulates (through herbivory and trampling of grass and shrublands). The *Biodiversity Guidebook* designates the AT as NDT5, a type that also includes all parkland subzones of the ESSF and MH; however, no quantitative estimates of disturbance attributes are provided for the NDT5 (B.C. Ministry of Forests and B.C. Ministry of Environment 1995).

Field-based Studies from British Columbia Specific to this Zone Little is known about vegetation dynamics of AT communities in British Columbia, particularly regarding the spatial and temporal attributes of natural disturbances. Douglas and Bliss (1977) briefly summarize research in British Columbia and Washington State up until the mid-1970s; no further studies specific to the AT appear to have been published since (see also Hamilton 1983, cited by Pojar and Stewart 1991a, p. 264).

However, most of the disturbance agents active in the subalpine BEC zones (see reviews of MH, SWB, and ESSF) likely affect the AT as well. For example, Parfett et al.'s (1995) study of western hemlock looper indicates that a significant proportion of defoliation between 1911 and 1994 (14.1% of the total defoliated area) was located in the AT. In the Mackenzie and Fort St. James forest districts, 4% of the total area defoliated by 2-year-cycle spruce budworm between 1985 and 1997 occurred in AT subalpine fir stands (Shand et al. 1999).

Whitebark pine is a high-elevation tree species of particular concern as it is declining over much of its range in North America. Several studies have linked its threatened survival to the combined effects of white pine blister rust, pine beetle epidemics, fire suppression, and climate change (Kendall and Arno 1990; Antos 1998; Campbell and Antos 2000).

Field-based Studies from Similar Ecosystems (United States, Alberta, Others) An extensive body of published studies has examined plant dynamics in subalpine and alpine regions of the U.S. Cascades and Rocky Mountains (e.g., Woodward et al. 1995; Rochefort and Peterson 1996). However, only a few papers directly address natural disturbances, such as frost heaving and snowcreep (Edwards 1980; Evans and Fonda 1990), desiccation-induced loss of foliage (Cairns 2001), and the effects of wildfire (Kuramoto and Bliss 1970; Douglas and Ballard 1971; Bollinger 1973; Agee and Smith 1984; Little et al. 1994). With the exception of Cairns (2001), who observed an average of 9% of *Abies lasiocarpa* krummholz canopy mortality during one winter, none of the studies quantitatively estimates disturbance dynamics.

Two commonly cited sources regarding the frequency of subalpine fires in interior western North America (Fryer and Johnson 1988; Agee 1993) state that fires tended to be infrequent (100–300+ yr) and driven by extreme weather events. Intervals between fires in the coastal subalpine can be from centuries to millennia (Lertzman et al. 2002). It is unclear, however, whether these estimates in the subalpine apply to the AT zone as well. Tree regeneration after fire appears to be largely unpredictable and only partially correlated with time since disturbance or climate (Agee and Smith 1984). Instead, facilitation (i.e., positive interactions of neighbouring plants) might be particularly important for successional dynamics in high-elevation forest ecosystems (Callaway 1998). In general, fire is considered to have beneficial effects on the persistence of individual tree species (e.g., whitebark pine [Kendall and Arno 1990]; also, see ESSF) as well as the diversity of krummholz and heath communities (Douglas and Ballard 1971).

Boreal White and Black Spruce Zone

The Boreal White and Black Spruce zone (BWBS) is part of the most widespread forest type in Canada (DeLong et al. 1991). In British Columbia, it is found at low elevations >54°N in the northeastern part of the province and in major valleys west of the northern Rockies. The SWB is typically the subalpine zone above the BWBS, although in the southern portion of the BWBS, it can be the ESSF. Winters are long and cold (mean temperatures <0°C for 5–7 months, annual precipitation 330–570 mm), growing seasons are short, and the ground is frozen for a large portion of the year.

The current version of British Columbia's biogeoclimatic (BEC) system differentiates five BWBS subzones with a total of nine variants (B.C. Ministry of Forests 2001). The *Biodiversity Guidebook* describes the four subzones of the BWBS as NDT3, with mean return intervals of stand-replacing events ranging from 100 years for BWBS with a prominent deciduous component to 125 years for BWBS with a prominent coniferous component. Establishment after fire typically occurs for up to 50 years by early seral species, such as trembling aspen, paper birch, and lodgepole pine (Hawkes 1982). White spruce, black spruce, and subalpine fir also establish after a fire, but dominate the stand later in succession (Parminter 1983b).

Fires drive disturbance dynamics in boreal forests and can be highly variable in their frequency, size, and severity, responding to landscape patterns and climate (Cumming 2000). Black spruce dominates on wet sites, and lodgepole pine on dry sites—both forest types conform to a relatively simple model of stand development after stand-replacing fires (Andison and Kimmins 1999). However, on mesic sites, successional pathways are much less predictable and the timing, severity, and size of disturbances are important for determining stand development (Parminter 1983a, 1983b; Andison and Kimmins 1999). However, not all parts of the boreal forest are driven by frequent stand-replacing fires, and gap dynamics, even in aspen stands, can maintain relatively old forests on the boreal landscape (e.g., boreal mixedwood in Alberta [Cumming 2000], and southern boreal forest in Minnesota [Frelich and Reich 1998]).

Besides mixed- to high-severity fires, other influential disturbance agents in the BWBS include wind and ice storms; spruce and western balsam bark beetle; defoliators, such as eastern spruce budworm and forest tent caterpillar; tomentosus root rot; root-collar weevils; and pine stem rusts (Wong 2001).

Field-based Studies from British Columbia Specific to this Zone Fire cycles of stand-replacing events in the BWBSdk in the Prince George Forest Region are estimated to range from 263 to 455 years (mean 333 yr) (DeLong 1998)[1]—much longer than the guidelines in the current *Biodiversity Guidebook* and those determined for north and central Alberta (see section below). See also work done by Francis et al. (1999, cited by Reid 2003; Table 1). Both small and large disturbance patches result: 23% of the disturbed area was in patches >1000 ha and 19% was in patches <100 ha in 1910–1930 (DeLong 1998).

In the Mackenzie Timber Supply Area (TSA), fire regimes in watersheds containing BWBSdk were associated with elevation, aspect, and valley orientation (Rogeau 2001). Air photo interpretation (photo dates

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[1] Fire cycles were determined using the proportion of area in forest inventory age classes 3 and 4 (41–80 yr) to avoid uncertainty in stand origin (natural fire vs. suppressed fire or logging) and uncertainty in the area in older age classes that may have reburned in subsequent fires (DeLong 1998). The fire cycles were determined for 1920–1960s and may not reflect historic intervals.

1942–1952) showed spatial subdivisions of several different fire regimes associated with broad terrain units and varying levels of vegetation complexity, which are considered to indicate the varying burn intensity and degree of overlap in wildfires (Rogeau 2001). Rogeau (2001) estimated historic fire cycles using landscape disturbance model, STANDOR. However, calibration and verification of the model were not provided and results summarized in Table 1 should be interpreted carefully. Of the fires observable on the 1950s air photos, approximately 60% were <1000 ha but these were responsible for only 9% of the area burned. Of the 20 largest wildfires recorded in the province since the 1920s, 14 of them have burned in the BWBS (J. Parminter, B. C. Ministry of Forests, Research Branch, pers. comm., 2003).

In British Columbia, eastern spruce budworm is associated primarily with the boreal forest; dendrochronological evidence in BWBS stands in the Liard River area suggests that defoliation occurred periodically five times since 1869 every 14–28 years (Shore and Alfaro 1986). Depending on the degree of defoliation and length of outbreak, this defoliator can cause average mortality of 1.5–6%/yr of white spruce in a stand (recorded in 12 BWBS stands after an outbreak in 1992–1997 [Alfaro et al. 2001]).

Field-based studies from similar ecosystems (United States, Alberta, others) Estimated fire cycles for coniferous-dominated boreal forests in Canada range from <100 to about 500 years (Payette 1992). Because these forests vary in seral communities and regional climate, we will focus on research in the boreal forest most similar to British Columbia, found in the Yukon, Alberta, and Saskatchewan.

Mean fire intervals ranged from 133 to 234 years in the boreal forest in Kluane National Park, Yukon (Hawkes 1982). This was determined from intervals between fire scars and intervals between scars and the stand origin date corrected for regeneration delay. Average fire size between 1850 and 1940, mapped from aerial photographs and aerial surveys, ranged from 140 to 1600 ha.

In the 48 000-ha Shakwak Trench close to Kluane National Park, fire cycles were longer, ranging from 300 to 350 years (Francis 1996).[2] However, similar to fire regimes described in the Mackenzie TSA boreal forest by Rogeau (2001), fire regimes appear to differ between certain classes of slope, elevation, and aspect in the Shakwak Trench (Francis 1996). Old forest >300 years occurred on steep north and east aspects, while frequently burned areas were associated with south and west aspects. In the Trench, 52% of the area showed no recent fire evidence. When fires were individually reconstructed, the total area burned since 1800 amounts to 78% of the forested area (some areas burning up to five or six times and others not at all). Fire size varied (average = 458 ha; standard deviation = 824 ha) and its distribution was dominated by a few large fires.

For the boreal forest with a substantial deciduous component, the paleoecological record of charcoal in lake sediment in northern Alberta suggests that over 840 years the mean fire interval was about 69 years, with no clear shifts in fire frequency during this time (Larsen and MacDonald 1998). However, a decline in fire frequency and a coinciding increase in aspen pollen was found in lake sediment during the Medieval Warm Period in Elk Island National Park, Alberta (Campbell and Campbell 2000). The authors hypothesize that declining groundwater levels during the warm period increased aspen over more fire-prone shrub birch, leading to the counter-intuitive observation of decreased fire during warmer and drier climatic periods.

Estimates of the fire cycle in northern Alberta, using age structure from forest inventories, range from 46 years in the pre-suppression era (mean annual burn rate = 2.2% [Murphy 1985]) to 60 years (1.67% [Van Wagner 1978, reviewed by Cumming 2000]). Because the method used to determine the fire cycle (Method 1-A [Van Wagner 1978]) is highly dependent on adequate sampling of old stands, using the forest inventory for this method is problematic.

In the lower and upper boreal zones in the Foothills Model Forest of Alberta, disturbance rates since the 1800s included periods of high and low fire activity. During the latter, disturbance rates were much lower than those listed above (Andison 2000). Reconstruction of disturbance rates over time was done by the Rollback Method (see Part 2, this report, for details). Between 1810 and 1930, fires burned on average 2% (range 0.3–3.8%) of the lower foothills and ~1.6% (range 0.05–2.9%) of the upper foothills annually.

Weir et al. (2000) estimated fire cycles before 1890 to be very short: 15 years (95% confidence interval

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[2] Francis (1996) used a cumulative time-since-fire distribution of fires since 1700, which were individually reconstructed with field sampling. He cautions, however, about violating the assumptions of spatially homogeneous fire regimes.

[CI] = 10–35 yr) in the northern part and 25 years (95% CI = 15–40 yr) in the southern part of Prince Albert National Park, Saskatchewan. From 1945 to the present, fire cycles have increased to 1745 and 645 years, respectively. The authors developed a time-since-fire map of 3461 km^2 by determining stand origin dates from fire scars, age of canopy trees, and dates of growth release in adjacent stands. Fire cycles were determined with the maximum likelihood estimate procedure (Method 1-B; see also Reed et al. 1998). Results based on an intensive effort such as this give a much higher level of confidence than those based on standard forest inventories (see discussion in Andison 1999).

Cumming (1997, cited by Cumming et al. 2000) determined a comparatively long fire cycle of 244 years (mean annual burn rate of 0.41%) for the mixedwood boreal in northeastern Alberta. He used a 54-year record of mapped fires, corrected for the effect of fire suppression by a nonparametric analysis of recent changes in the fire size distribution. Mean annual burn rates varied between stand types: 0.27% for aspen leading, 0.67% for white spruce leading, 0.60% for black spruce leading, and 0.31% for mixed deciduous and coniferous stands (Cumming 2001). Other studies have estimated burn rates to be more frequent for aspen stands (e.g., Larsen 1997). However, evidence of uneven-aged aspen stands and gap dynamics in boreal mixedwood stands supports the hypothesis of a longer fire cycle (Cumming et al. 2000).

Differences of an order of magnitude in fire cycle estimates between Cumming (1997, cited by Cumming et al. 2000) and some other studies (Van Wagner 1978; Larsen and MacDonald 1998; Weir et al. 2000) could be due to inappropriate analyses, too short a time period used by Cumming, or inherent differences in different portions of the boreal mixedwood. On the other hand, Cumming's estimates are similar to those determined for the Foothills Model Forest, the Yukon, and northeastern British Columbia.

Between 1970 and 1983, fires that burned in boreal forests of northern Alberta ranged from 21 to 17 770 ha ($n = 69$ fires) (Eberhardt and Woodard 1987). The size of remnant patches (or islands) within these fires increased with fire size; median remnant size ranged from 2.3 to 9.4 ha. In contrast, preliminary data from the Foothills Model Forest found that remnant size did not increase with fire size; instead, sizes of remnant patches were highly variable among fires and correlated with fire intensity (Cumming 2000). Both studies found that island density increased with fire size—the number of islands ranged from 0 to 0.96 islands/100 ha (Eberhardt and Woodard 1987). Andison (2001) presents a conceptual model of the "morphology of a fire"; it incorporates numerous burned patches, "true islands," and "matrix patches" still connected to the surrounding forest matrix. However, burning patterns within these fires were likely affected by fire suppression. In general, islands tend to be composed of forest types with lower burn rates, such as aspen or mixed deciduous/conifer types (Smyth 1999, cited by Cumming 2000).

Simulation Modelling of Natural Disturbances

Burn rates in the boreal mixedwood forest in northeastern Alberta are thought to be highly variable; mean annual burn rates varied from 0.5 to 2% over a simulation period of 230 years (Armstrong 1999). These estimates are similar to disturbance rates determined from age-class distributions in the Foothills Model Forest (Andison 2000). Consequently, methods that assume equilibrium age distributions to determine fire cycles in boreal forests (i.e., constant burn rates) may give inaccurate results.

A simulation of the range in natural variability expected in seral stages in the Foothills Model Forest concluded that current hardwood and mature spruce forest types were more extensive than in the past few centuries due to recent fire suppression (Andison 2000). Cumming (2001) developed a model based on the distribution of recent fire sizes in the same region. It demonstrates that the expected size of a fire is positively related to the amount of jack pine and negatively related to recently logged or burned areas.

Because the impact of global warming is expected to be greatest at the northern latitudes (Intergovernmental Panel on Climate Change 2001), several studies have tried to model the effects of various scenarios of climate change on fires in boreal ecosystems. In a scenario of a doubling in carbon dioxide concentrations in the atmosphere, lightning and lightning ignitions are predicted to increase, and the fire season lengthen by 22% on average in Canada (Flannigan et al. 2001). In the boreal forest in west-central Alberta, the fine fuel moisture code is predicted to increase by one point (unit) and spatially explicit simulations predict that fire frequency will increase while overall forest volume will decrease (Li et al. 2000). However, regional variability in model predictions regarding the effect of climate change on the Canadian Forest

Fire Weather Index is significant. The index is predicted to increase over much of the boreal forest, whereas in eastern Canada and in northern interior British Columbia and the Yukon it is predicted to decrease (Flannigan et al. 2001).

Technical comments

- The observation that disturbance rates have varied over time suggests that age distributions are not in equilibrium in some boreal forests. Consequently, Methods 1-B or 1-C (see Part 2, this report) should be chosen.
- Using the proportion of area in a certain age class to determine disturbance rates or patch size distributions is appropriate only where disturbance intervals are very long (e.g., Hawkes et al. 1997), or where the analysis has been restricted to age classes not likely to have been logged, originated from suppressed fires, or reburned by subsequent fires (e.g., DeLong 1998), or where reburns by subsequent fires have been modelled or sampled in the field (e.g., Andison 1996).

Bunchgrass Zone

The Bunchgrass zone (BG) contains the grasslands in the southern interior of British Columbia from valley bottoms up to 700–1000 m (Nicholson et al. 1991). The BG usually borders the PP, but in some locations adjoins the IDF. Summers are dry and hot and winters are moderately cold, depending on topography and latitude. Summer drought and/or frequent, low-severity fires are thought to be responsible for the dominance of grasses in this zone.

The current version of British Columbia's BEC system differentiates two BG subzones with a total of five variants (B.C. Ministry of Forests 2001). The *Biodiversity Guidebook* designates both subzones as NDT4, with frequent, stand-maintaining events of mean return intervals of 4–50 years.

Field-based Studies from British Columbia Specific to this Zone In one site in the BGxh3 in the Churn Creek Protected Area, low-severity fires as recorded on fire-scarred trees burned on average every 19 years (Blackwell et al. 2001). Fires could be even more frequent than this estimate as the BG is primarily not forested and many fires were likely not intense enough to scar the few trees.

The importance of low-severity fires and climate in maintaining grassland is suggested by patterns in the paleoecological sagebrush pollen record and observations of recent tree encroachment into grasslands. Paleoecological records of sagebrush pollen in lake sediment indicate that the BG zone was at its greatest extent in British Columbia in the early Holocene (10 000–8000 before present), a period considered to be dry and warm with a high fire frequency (Hebda 1995). Modern tree encroachment into grasslands in the Cariboo and Nelson forest regions' Interior Douglas-fir (IDF) zone, as recorded from comparing historic air photos with 1990s photos and examining patterns of tree establishment, coincide with modern fire exclusion and grazing (Strang and Parminter 1980; Gayton 1997; Ross 1997, 2000). In BG and PP subzones in the South Okanagan and Lower Similkameen valleys, invasion and ingrowth of conifers into grasslands or open forest significantly increased in unburned sites when comparing 1938–1985 and 1985–1996 air photo pairs (Turner and Krannitz 2001). Encroachment in a meadow containing a disjunct ponderosa pine ecosystem in the upper Skagit Valley (IDFww) was linked to the absence of frequent First Nations fires and shallow spring snowpacks since the 1970s (Lepofsky et al. 2000).

Field-based Studies from Similar Ecosystems (United States, Alberta, Others) Similar paleoecological patterns have been found in the northern Great Plains (Camill and Clark 2000). Frequent fires and climate are also thought to be important for maintaining grasslands at the interface between ponderosa pine forests and grasslands in Colorado. Ponderosa pine has been able to establish and invade grasslands due to the lack of fires in the 1900s, increased grazing, and hypothesized climatic variation (Nystrom et al. 1998).

Simulation Modelling of Natural Disturbances Eng et al. (unpubl.) have built models of succession, fire, grazing, and forest harvesting to simulate change in the understorey seral stage across grasslands and forest near Dog Creek, south of Williams Lake, but these models have not been validated.

Coastal Douglas-fir Zone

The Coastal Douglas-fir zone (CDF) is limited to a small area lower than 150 m in elevation on the southern Mainland, a few islands in the Georgia Strait, and southeastern Vancouver Island. Most of the original forest was logged around 1900 (Nuszdorfer et al. 1991). The CDF borders the CWHxm1 at higher elevations and further inland. It lies in the rain shadow of the Vancouver Island Mountains and the Olympic Mountains. Thus, mean monthly temperatures are around 10°C and rarely fall below 0°C (Nuszdorfer et al. 1991). Mean annual precipitation ranges from 647 to 1263 mm; summers are dry and winters are mild and wet. The current version of British Columbia's BEC system lists only one subzone, the CDFmm (B.C. Ministry of Forests 2001). The *Biodiversity Guidebook* describes disturbances in the CDF as NDT2, with stand-replacing disturbances occurring at mean intervals of 200 years. Low-severity fires did occur, but are thought to have been ignited primarily by humans (J. Parminter, B.C. Ministry of Forests, Research Branch, pers. comm., 2002). For example, Garry oak meadows in the CDF were likely maintained by low-severity fires ignited by First Nations peoples. Fire sizes are thought to be relatively small, ranging from 1 to 500 ha (Parminter 1992). Disturbance dynamics likely resemble those in the CWHxm1.

Field-based Studies from British Columbia Specific to this Zone None known.

Field-based Studies from Similar Ecosystems (United States, Alberta, Others) Agee and Dunwiddie (1984) examined forest development and fire history on a small (4.5-ha) island in Puget Sound, Washington. Based on regeneration pulses of Douglas-fir (*Pseudotsuga menziesii*), bark char, and eyewitness accounts, they inferred a patchy, low- to mixed-intensity fire regime of approximately 80-year rotation. However, many of these fires appear to have been ignited by humans.

Simulation Modelling of Natural Disturbances None known.

Coastal Western Hemlock Zone

The Coastal Western Hemlock zone (CWH) occurs at low to mid elevations on Vancouver Island, the Queen Charlotte Islands, and the Coast Mountains up to southern Alaska (Pojar et al. 1991a). It adjoins the MH at high elevations. The CWH is the rainiest zone in British Columbia—mean annual precipitation ranges from 1000 to 4400 mm—with cool summers and mild winters. The current version of British Columbia's BEC system differentiates 11 CWH subzones with a total of 21 variants (B.C. Ministry of Forests 2001). The *Biodiversity Guidebook* describes the dry, moist, and wet sub-maritime subzones of the CWH as NDT2, with infrequent stand-replacing events occurring at mean intervals of 200 years. The remaining wet and very wet subzones are classified as NDT1, with rare, small, stand-replacing events at mean return intervals of 250 years. Some of the very wet subzones are listed as NDT3, where frequent stand-replacing windthrow events on exposed parts of the coast are estimated to occur with return intervals of 100 years.

The moist climate and frequent cyclonic storms strongly influence forest dynamics on the coast. Small canopy gaps of 10 trees or fewer, caused primarily by wind, in association with pathogens, such as rot and hemlock dwarf mistletoe, are the primary mode of disturbance over most of the landscape (Alaback 1991; Hennon 1995; Lertzman et al. 1996; Dorner and Wong 2002). In susceptible parts of the CWH, geomorphic disturbances are the most frequent stand-replacing events, although wind, flooding, and fire occasionally create larger canopy openings (Banner et al. 1983; Septer and Schwab 1995; Pearson 2000, 2003). Other disturbance agents, such as feeding by ungulates, porcupines, weevils, and insect defoliators, play a minor role (Dorner and Wong 2002), but in managed stands can significantly change forest structure and composition (e.g., Sullivan et al. 1986).

Field-based Studies from British Columbia Specific to this Zone The CWH established over most of southern Vancouver Island during the moistening and cooling trends of the mid-Holocene (7000–4000 years before present [Brown and Hebda 1998]). A coinciding decrease in charcoal accumulation in the sediment of five lakes on Vancouver Island suggests a decreasing role for forest fires in these forests relative to the early Holocene. However, during the mid- to late Holocene the role of fire appears to vary with location: fire-free intervals of about 3000 years were observed in western moister sites, whereas charcoal was continuously deposited over time in lakes on the drier eastern side of the island (Brown and Hebda 1998).

Many existing stands in the CWH are thought to have originated after mixed- to high-severity fires. This hypothesis is supported by widespread evidence of cohorts of old Douglas-fir, a long-lived seral species that establishes almost exclusively following fire (Green et al. 1999). However, Douglas-fir seems also able to regenerate in larger gaps of old stands (Franklin et al. 2002). The date of establishment of old Douglas-fir cohorts in CWH stands on northern Vancouver Island suggests that fires occurred nearly every century for the last 1000 years (Schmidt 1970, cited by Parminter 1990; Green et al. 1999). Eis (1962, cited by Green et al. 1999) used the same line of evidence to suggest fires occurred every century (since 1540) in the Coquitlam and Seymour watersheds in the Lower Mainland. In addition to Douglas-fir, both western hemlock and western redcedar can be found as post-fire early seral species in the CWH (Arsenault and Bradfield 1995). Daniels et al. (1995) found coinciding peaks of regeneration of western redcedar in stands in the Capilano, Seymour, and Coquitlam watersheds, and suggested that they originated from regionally co-ordinated pulses of fire disturbance 500–900 years ago.

In the CWHvm1 in the Capilano watershed (Lower Mainland), the establishment dates of Douglas-fir cohorts on 17 sites suggests that pre-settlement fire *episodes*[3] occurred about 1207, 1307, 1397, 1597, and 1687 (time-since-fire ranges from 33 to 1200 yr [Green et al. 1999]). On seven sites, multiple cohorts were found, suggesting that partial-replacement fires occurred at return intervals of 200–450 years (mean = 345 yr). The area influenced by these fire episodes included fragments of 10–1048 ha in the watershed. However, these numbers do not represent a size distribution of individual fires nor do they account for areas that have reburned. Green et al. (1999) conclude that widespread fire episodes in the CWH are likely to occur, given the suggested regional-level climatic controls on fire years (Agee 1993). However, almost half of the Capilano watershed was not sampled, as it was composed of late-successional western hemlock and western redcedar stands. These stands may also have originated from fire but that early seral Douglas-fir cohorts have disappeared; if so, it would increase the range of time-since-fire for the watershed.

Gavin (2000, 2003) determined point estimates of time-since-fire from tree ages, soil charcoal, and return intervals of peaks of charcoal in lake sediments to reconstruct the fire history in the CWHvm1 in Clayoquot Valley on western Vancouver Island. Time-since-fire in 83 sites along a 200-m grid ranged from 64 to 12 220 years before present. Fire extent rarely exceeded 250 m in diameter in this study, although the sampling strategy may have been unable to detect fires that spread to higher elevations. Area return intervals of fires occurring within 250 m of Clayoquot Lake increased from 50 to 350 years from AD 200–900 to AD 1100–present (Gavin 2000; Table 1). The shift from frequent to infrequent fires suggests an abrupt change in the controls of forest fire and coincides with the onset of the Little Ice Age. Fires tended to burn only certain areas as only 63% of the area around the lake burned at least once between AD 200 to the present.

Fire return intervals in the CWHvm1 can vary greatly with topography—median time-since-fire was significantly six times greater on terraces (median ca. 4500 yr) than hillslopes (median ca. 750 yr) in Clayoquot Valley (Gavin 2000). Approximately 20% of the sampling sites were on low fire-susceptibility landforms (northerly aspects and low terraces) and had no evidence of burning in over 6000 years. All the sites on high-susceptibility landforms, such as south aspects, had burned within the last 800 years. Time-since-fire also varied somewhat with forest type—for example, cedar–salal type (median <500 yr) had a narrower range of intervals than other cedar–hemlock, hemlock–fir, and Sitka spruce forest types.

The occurrence of isolated patches of Douglas-fir on specific topographic sites (Green et al. 1999; Gavin 2000) and the requirement of a local seed source for Douglas-fir regeneration suggests that portions of the CWH must burn at intervals less than the 700–800 year lifespan of Douglas-fir to maintain the species on the landscape. The association between time-since-fire and topography suggests that fires repeatedly burn certain sites, while other sites have an extremely low fire frequency that permits late-successional forest communities to develop.

In the CWH, the most frequent stand-replacing events are geomorphic disturbances, such as rockslides, debris flows, and avalanches (Banner et al. 1989; Pearson 2003). These disturbances are confined to specific locations and small areas; in Clayoquot Valley, landslides (mostly rockslides) and avalanches occupied 2.4% each of the total area (Pearson 2000). On the central coast, air photo interpretation of 1.5 million ha (offering approximately 140 yr of disturbance evidence) found that fire burned a single watershed in the driest part of the study area, windthrow was limited to isolated patches on exposed outer coast islands, and geomorphic disturbances

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[3] Fire episodes are not distinct fires but rather periods of time that may have included several fires in several locations. In this study, obtaining exact dates of fires was not possible because of the wide range in establishment dates (due to uncertainty about the ages of large trees) and because tree establishment after fire can take up to 60 years (Green et al. 1999). Time-since-fire at each sampling location was not given.

(including landslides, avalanches, and floods) dominated elsewhere (Pearson 2003). All of these stand-replacing disturbances affected 0.02% of forested area per year—for an estimated return interval of 4500 years (Pearson 2003). Debris flow frequency varies between unlogged watersheds from 0.0037 slides per km^2/yr in Clayoquot Valley (Jakob 2000) to 0.065 slides per km^2/yr on the Queen Charlotte Islands (Schwab [editor] 1998).[4] The frequency of debris flows in logged terrain was approximately nine times higher than the natural rate in Clayoquot Valley (Jakob 2000) and 15 times higher on the Queen Charlotte Islands (Schwab [editor] 1998).

Records of catastrophic wind events causing partial to complete blowdown of up to several hundred hectares on Vancouver Island, north coastal British Columbia, and southeastern Alaska (Keenan 1993; Mitchell 1998; Nowacki and Kramer 1998; Kramer et al. 2001) indicate that these events occur yet tend to be episodic. Field and historical air photo evidence from Vancouver Island and the central coast suggests that severe blowdown is fairly rare in those areas (Lertzman et al. 1996; Pearson 2000, 2003). A reanalysis of blowdown data in the North Coast Forest District from Mitchell (1998) indicates that an annual proportion of approximately 0.03% of the operable area was disturbed by wind between 1960 and 1996 (Dorner and Wong 2002). If calculated over the entire North Coast Forest District, this corresponds to a return interval of approximately 3000 years. If blowdown occurred only in wind-exposed portions of the landscape, return intervals would be shorter; for example, 300 years if only 10% of the landscape is considered susceptible. Although Mitchell (1998) found no evidence that blowdown was associated with particular areas or exposures, studies from southeast Alaska concur that catastrophic wind disturbance is concentrated in topographically exposed areas and is frequent enough in exposed forests (at relatively short intervals of 50–300 yr) to prevent all-aged stands from developing (Nowacki and Kramer 1998; Kramer et al. 2001).

Without fire, geomorphic, and wind disturbances, fine-scale processes causing the non-simultaneous death of one to eight trees ("gapmakers") and creating gaps in the canopy tend to dominate forest dynamics. As a result, such stands tend to be multi-aged (Beese and Sandford 1992; Daniels et al. 1995; Lertzman et al. 1996). An average of 30% of the forest area sampled in the Tofino Creek CWHvm1 and vm2 landscape was influenced by edaphic (14%; those caused by rock outcrops or small wetlands) or developmental canopy gaps (16%; those caused by fallen trees) (Lertzman et al. 1996). Standing death or stem snap of canopy dominants infected with stem rot was the principal mode of gap formation; uprooting was more common on relatively dry and wet sites (Lertzman et al. 1996). The amount of area in gaps did not differ between mature (100–250) and old-growth (>250 yr) forest; however, old-growth stands had smaller gaps than mature stands—this may reflect different developmental trajectories. Research elsewhere on Vancouver Island suggests that two distinct communities can exist on similar sites, if they had different disturbance histories; for example, windfirm cedar–hemlock and windthrow-prone hemlock– amabilis fir (Prescott et al. 1993; Keenan et al. 1994, cited by Lertzman et al. 1996).

In three sites in old-growth CWH on the Lower Mainland and Vancouver Island, 38% of the forest area was in developmental canopy gaps, and roughly equal proportions of gapmakers died standing or were uprooted (Arsenault 1995). Differences in the proportion of uprooted gapmakers between these sites and those in Tofino Creek suggest that windthrow varies across the CWH. Without large-scale disturbances, turnover rates of gaps in CWHvm1 and vm2 forests—that is, the average time span between successive disturbances in a stand—range from 313 to 1379 years on western Vancouver Island (Lertzman et al. 1996).[5]

Field-based Studies from Similar Ecosystems (United States, Alberta, Others) Fire history studies in similar forests on the Olympic Peninsula (Huff 1995) and in Mount Rainier National Park (Hemstrom and Franklin 1982) found similar long intervals between stand-replacing fires. In the central Oregon Coast Range, 27 fire episodes were recorded over 516 years and 137 500 ha, based on stratified sampling of Douglas-fir stumps in clearcuts (Impara 1997). Only six of these episodes were of high severity; most episodes affected few sites and were of low severity. Franklin et al. (2002) present a conceptual model of forest development for the Douglas-fir–western hemlock forests of the Pacific Northwest that incorporates the severity of initiating disturbances and the spatial structure of a stand.

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[4] Unknown if these are all natural slides.

[5] Estimates of turnover rates depend on the time estimated to fill a gap. In this study, 50–200 years were assumed.

Gap dynamics have been studied in Douglas-fir–dominated forests in western Oregon and Washington (e.g., Spies et al. 1990). The annual rate of gap creation was 0.7% of area in mature (100–150 yr) stands and 0.2% in old growth (>200 yr), as estimated from mortality records in 34 permanent plots (Spies et al. 1990). Developmental canopy gaps covered 18.2% of the area in mature stands and 13.1% area in old-growth stands. Gaps in old-growth stands were larger than in mature stands. Median gap sizes were 85 m^2 (two or more trees) in old growth and 19 m^2 (one tree) in mature stands. This result contrasts with those of Lertzman et al. (1996) in the CWHvm1 in British Columbia.

Simulation Modelling of Natural Disturbances
None known.

Technical comments

- Disturbance history is difficult to reconstruct in the CWH because much of it has been logged. The few lines of evidence that are available are difficult to interpret because (1) there are few fire-scarred trees and even-aged stands; (2) fire intervals can be longer than the lifespan of early seral Douglas-fir; and (3) radiocarbon ages of soil charcoal can overestimate fire ages by 100–400 years because of built-in error from the age of the wood at the time it burned—this precludes detection and resolution of fire return intervals <450 years with this method (Gavin 2001).

Engelmann Spruce–Subalpine Fir Zone

The Engelmann Spruce–Subalpine Fir zone (ESSF) occupies the highest forested elevations in most of British Columbia's mountain ranges. It lies below the Alpine Tundra zone (AT) and above the ICH, MS, or SBS zones, typically at elevations between 1200 and 2300 m (Coupé et al. 1991). Its northern boundaries are formed by the SWB and BWBS zones. Ecosystem types similar to the ESSF occur in Alberta, the U.S. Pacific Northwest, and the northern and central U.S. Rocky Mountain states (Varga and Klinka 2001). Given its large geographic range, ESSF ecosystems experience a variety of climatic conditions. Generally, the climate is cold and moist with long snowy winters but annual precipitation ranges from 400 mm on drier sites to 2000 mm in wetter areas (Coupé et al. 1991). Forests in the ESSF span the gradient from continuous cover to subalpine parkland and 15 of its 17 recognized subzones in British Columbia are subdivided into forested and parkland types. A total of 50 variants attest to the ecological diversity and geographic extent of the ESSF (B.C. Ministry of Forests 2001).

Wildfires in the ESSF are considered to be relatively infrequent. They tend to be stand replacing due to the major tree species' high susceptibility to fire damage (Fischer and Bradley 1987). However, fire-initiated stands are not necessarily even-aged, as post-disturbance recruitment can take many decades (Jull 1983; Parish et al. 1999). Two other important abiotic disturbance agents in the ESSF are windthrow and avalanches (e.g., Veblen et al. 1991; Ferguson and Pope 2001; Sagar and Jull 2001). Of the many biotic agents that weaken or kill trees in this zone, bark beetles, 2-year-cycle budworm, western hemlock looper, decay fungi, and root rot are considered to be the most important (Lindgren and Lewis 1997). In the southeastern subzones of the ESSF, whitebark pine historically formed an important overstorey component but today is threatened due to a combination of fire exclusion, blister rust, and mountain pine beetle (Campbell and Antos 2000; Stoffels 2000; Zeglen 2002) (see also AT zone).

ESSF subzones encompass four of the five natural disturbance types distinguished in the *Biodiversity Guidebook*, with stand-initiating events assumed to be occurring on average every 150 years (in drier subzones) to 350 years (in wetter subzones) (B.C. Ministry of Forests and BC Environment 1995).

Field-based Studies from British Columbia Specific to this Zone For several ESSF subzones in central and northern British Columbia, attributes of stand-replacing disturbances have been estimated by using forest inventory data as time-since-disturbance maps (Hawkes et al. 1997; Steventon 1997, 2001; DeLong 1998). The four studies concluded that mean disturbance return intervals for the ESSF appear to be longer than suggested by the *Biodiversity Guidebook*, in some cases by several centuries (e.g., Hawkes et al. 1997). Also, disturbance rates were correlated with climatic conditions, with wetter and more snow-prone subzones exhibiting longer return intervals (e.g., Steventon 1997). Between these studies, the range of return intervals spans from a low of 219 years in the Prince Rupert Forest Region's ESSFmc (Steventon 2001)[6] to a high of 794 years in the Prince George

Forest Region's ESSFwk2/wc3 (Hawkes et al. 1997). The other subzones under investigation, ESSFmkwv (Steventon 1997, 2001) and ESSFmv (DeLong 1998),[7] are intermediate in their estimated return intervals.

General conclusions from these studies are that (1) most ESSF landscapes in north-central British Columbia are dominated by older forests; (2) disturbance rates have changed over time; and (3) patch size distributions vary considerably among study areas (e.g., Hawkes et al. 1997 vs. DeLong 1998), though all examined subzones were strongly influenced by large disturbance events >1000 ha.

For the southern ESSF subzones, fire history has been studied in several of the Rocky Mountain National Parks (Masters 1990; Tymstra 1991; Rogeau 1994, 1996, 2000; Van Wagner 1995; Weir et al. 1995). The specific purpose of most of these studies was to determine changes in fire frequency over time to make inferences about potential causal factors (e.g., humans vs. location vs. climate). Again, time-since-fire distributions were derived from stand origin maps, though in these cases maps were developed specifically for these studies and supported by extensive fieldwork.

Fire frequency estimates appear to differ significantly from those of north-central British Columbia. Fires appear to have been much more common in the southern Rocky Mountains, with fire cycles ranging from 45 to 266 years (Van Wagner 1995; Rogeau 2000). To some extent, these relatively high return intervals are artifacts of pooling drier valley-bottom ecosystem types with wetter subalpine forests. On the other hand, ESSF subzones of the southern Rockies are drier (ESSFdk) than in north-central British Columbia and return intervals can be expected to be shorter (the *Biodiversity Guidebook* estimates a mean event interval of 150 years for the ESSFdk).

Frequent, mixed-severity fire regimes may characterize ESSF stands on south aspects adjacent to the Interior Douglas-fir (IDF) zone (Gray et al. 2002). Preliminary data from fire-scarred whitebark pine in an ESSFmw site near Pemberton indicate a very short mean fire interval of 21 years for the period 1780–1930 (R.W. Gray, R.W. Gray Consulting Ltd., pers. comm., 2002). The author suggests that First Nations peoples probably ignited many of the fires.

The debate appears unresolved regarding whether fire intervals in subalpine forests have increased and what the driving factors might have been (e.g., Johnson and Larsen 1991 vs. Weir et al. 1995). This highlights the strong influence of methodological assumptions as well as the uncertainties associated with extrapolating spatially and temporally from a limited set of data.

Dorner (2001) used stand-age maps of the Arrow IFPA to estimate pre-settlement (1700–1860) disturbance return intervals. For the ESSFwc1, intervals range from 90 to 807 years and for the ESSFwc4 from 105 to 508 years.[8] Her results showed that disturbance rates were not stationary during the past, and that the early 20th century was a period of high disturbance rates, followed by a decline during the second half. While this pattern was especially strong in the ESSFwc4, it was absent for the ESSFwc1, where disturbance frequency was low during the first part of the 20th century (Dorner 2001). Note that Part 3 of this report contains our re-analysis of the Arrow Forest District data.

Even stand-replacing fires often have heterogeneous burn severity and spatial coverage. As part of a larger study, Stuart-Smith and Hendry (1998) mapped residual trees and patches in seven fires in the ESSFdk and ESSFmw subzones of the Nelson Forest Region. They found that residual patch size varied greatly (1–100 ha) while patch size appeared uncorrelated with fire size. Residual patches tended to occur near streams but did not have consistent affiliations with other topographic attributes. Larger tree islands sometimes contained spruce and fir but most of the smaller patches and all individual wildfire survivors were either Douglas-fir or western larch (Stuart-Smith and Hendry 1998).

Using similar methods, Brochez et al. (2001) mapped seven wildfires and their residual patches in the Morice and Lakes TSAs in west-central British Columbia. Sizes of unburned patches ranged from ~1 to 245 ha. Their methods-oriented report provides detailed tables about each of the mapped fires (including four in the ESSFmc and one in the ESSFmv) but few summary statistics or conclusions.

[6] Determined using forest inventory age classes 3–7, with no correction for reburns in older age classes.

[7] These intervals were determined using forest inventory age classes 3 and 4 (41–80 yr) to avoid uncertainty in stand origin (natural fires vs. logging or suppressed fires) and uncertainty in area in older age classes that may have reburned in subsequent fires (DeLong 1998).

[8] Determined by Rollback Method 1-C (see Part 2, this report) using FIP data, accounting for expected error in FIP ages and assumptions about what was previously harvested. Note that the wide range in the estimates is partially a result of pooling results for several different scenarios; individual scenarios are listed in Table 1.

A number of recently published field studies have characterized the structure and development of unmanaged ESSF stands. Most of the examined stands show evidence of initiation by fire (but see Antos and Parish 2002) and a subsequent transition to fine-scale, patchy mortality and regeneration caused by senescence or disturbances of limited severity (e.g., budworm, bark beetles, or windthrow). Maximum stand ages (i.e., fire-free periods) ranged from ~300 to >460 years. However, despite similarities in stand structure and species composition, the age-class distributions of the study sites show large differences, suggesting a variety of site-specific developmental pathways (Quesnel and Pinnell 1998; Parish 2001). However, most ESSF stand structure studies in British Columbia have focused on sites dominated by subalpine fir (with the exception of Holt 2000) and together cover only six of the 16 ESSF subzones: ESSFwc4 (Quesnel and Pinnell 1998); ESSFwm (Holt 2000); ESSFmc (Varga and Klinka 2001); ESSFvv (Antos and Parish 2002); ESSFdc1 or ESSFxc (Parish 2001); and ESSFwc2 (Parish et al. 1999).

Little is known about the frequency and severity of windthrow disturbances in ESSF forests. Huggard et al. (1999, 2001) compared harvesting units in ESSFwc2 stands at Sicamous Creek against uncut controls. Their data suggest that wind and snow damage is a continuing source of tree death, is highly variable in annual rates, and causes variable types of damage (e.g., snapped vs. uprooted stems). During the 5-year analysis period, annual loss of basal area averaged 3.2% in subalpine fir and <0.5% in Engelmann spruce (Huggard et al. 2001). The authors conclude that the greater windfirmness of spruce helps to maintain the species in ESSF forests. The extent to which periodic severe wind storms act as agents of stand-replacing disturbances is unknown (see discussion in Sagar and Jull 2001).

Studies on insect disturbance in the ESSF have focused on 2-year-cycle spruce budworm (Shand et al. 1999; Zhang et al. 2001; Parish and Antos 2002; Zhang and Alfaro 2002) and western hemlock looper (Parfett et al. 1995; Daust and Price 2000). Dendrochronological data from a single stand in the ESSFdc1 or ESSFxc showed several 2-year-cycle spruce budworm–induced growth losses 30–45 years apart (Parish and Antos 2002). Using ring-width analyses, Zhang et al. (2001) estimated a 24- to 39-year frequency in the Fort St. James and Mackenzie forest districts during the past century. Their data also showed that outbreaks were synchronized across north-central British Columbia, probably due to a combination of stand susceptibility and weather conditions (Zhang and Alfaro 2002). A GIS-based analysis of defoliated stands in the same region showed that biogeoclimatic subzone was a good indicator of susceptibility to defoliation and that ESSFmc stands were more prone to defoliation than ESSFmv3 or ESSFmv4 (Shand et al. 1999). Over the entire province, outbreaks of western hemlock looper appear to be cyclic, occurring on average every 9 years (Parfett et al. 1995; Alfaro et al. 1999). Between 1911 and 1994, the ESSFvc and ESSFwk1 have been particularly affected (Parfett et al. 1995). Defoliator-induced growth reduction of affected trees can be significant and sustained; mortality is a function of the degree of defoliation (Alfaro et al. 1999).

A preliminary study of pathogenic organisms in the ESSFwc2 at Sicamous Creek found that root rot and decay fungi are important endemic pathogens that influence the ratio of fir and spruce overstorey trees (Merler 1996; see also Lewis and Lindgren 2000). In addition, Merler (1996) observed that small rodents had damaged the root systems of 89% of the subalpine fir trees sampled, but almost none of the spruce.

Field-based Studies from Similar Ecosystems (United States, Alberta, Others) Subalpine forests have been studied in both Alberta and the United States. It is difficult to determine how applicable the particular results are for ESSF ecosystems in British Columbia. However, many of these studies can provide researchers in British Columbia with working hypotheses and tested methods as a point of departure (e.g., Whipple and Dix 1979; Fischer and Bradley 1987; Johnson and Fryer 1989; Baker and Veblen 1990; Veblen et al. 1991; Rebertus et al. 1992; Woodard 1993; Agee 1994; Lynch 1998; Donnegan and Rebertus 1999; Andison 2000; Schellhaas et al. 2001).

Simulation Modelling of Natural Disturbances A timber supply modelling project for the Cassiar Iskut-Stikine LRMP has used fire return and size data to integrate natural disturbances and harvest activities (Olivotto Timber 1999). The study found that sustainable rates of timber harvesting are 25–40% lower in the presence of natural rates of disturbance than the standard Timber Supply Review (TSR) calculation without disturbances. Note, however, that the project lumped all CWH, ESSF, ICH, and SWB subzones in the study area into one "medium intensity burning" zone, and assigned this zone a mean fire return interval of 250 years (Olivotto Timber 1999). Moreover, the 250-year return interval was an input to, not a result of, the modelling project.

Technical comments

- Confidence intervals for disturbances, as determined by statistical analyses of forest inventory maps, can be very large. As a result, differences in results between scenarios based on different assumptions are sometimes greater than differences between subzones. For example, Steventon (2001) reports that 80% confidence intervals for estimated disturbance frequencies in the ESSFmk range from 153 to 1486 years (Steventon 2001; Table 1).
- The uncertainty associated with these estimates is largely due to the unknown level of error or bias in stand ages in the forest inventory (see also Part 3, this report).
- We are unaware of any study that has tried to quantify attributes of interactions between disturbance agents active in the ESSF. However, Lindgren and Lewis (1997) describe an important first step in this direction by developing a conceptual model of disturbance ecology for the SBS and ESSF forests in the McGregor Model Forest.

Interior Cedar–Hemlock Zone

The Interior Cedar–Hemlock zone is found at low to middle elevations (400–1500 m) below the ESSF in southeastern British Columbia and just east of the Coast Mountains in west-central British Columbia (Ketcheson et al. 1991). The zone extends south into eastern Washington, northern Idaho, and western Montana. The ICH has cool, wet winters (mean annual precipitation is 500–1200 mm) and warm, dry summers (temperature averages below 0°C for 2–5 months). The current version of British Columbia's BEC system differentiates 12 ICH subzones with a total of 24 variants and phases (B.C. Ministry of Forests 2001).

Disturbance regimes in the ICH are complex—the *Biodiversity Guidebook* describes four different natural disturbance types ranging from frequent, low-severity fires in the dry subzones to rare, stand-replacing fires in the wet and very wet subzones. Other disturbance agents are particularly influential in the ICH; for example, the ICH has the highest incidence of root rot relative to other biogeoclimatic zones (H. Merler, B.C. Ministry of Forests, Stewardship Resources, pers. comm., 2002). Influential disturbance agents include a combination of avalanches, bark beetles (mountain pine, Douglas-fir, spruce), defoliators (western spruce budworm, western blackheaded budworm, western hemlock looper), root rot (Armillaria, tomentosus, annosus, laminated), and minor agents, including weevils, adelgids, needle diseases, and dwarf mistletoe (Wong 2001).

Field-based Studies from British Columbia Specific to this Zone A preliminary analysis of charcoal deposits in lake sediment in the ICHmw2 and ESSFwc4 concludes that area return intervals ranged from 200 to 800 years (D. Gavin, preliminary data). These intervals are longer than fire cycles estimated for the ICHwk1 and ESSF in Glacier National Park; fire cycles for the park area are reported as 80 years between 1519 and 1760, and 110 years after 1760 (Johnson et al. 1990).[9] The periods of change were determined *a posteriori* from changes in slope in the time-since-fire distributions and hypothesized to be linked to the Little Ice Age (see Huggard and Arsenault 1999, 2001 and Reed and Johnson 1999 for a critique and debate of this method). Johnson et al. (1990) suggest that fire frequency has not decreased since fire suppression and that the entire park is under the same fire regime.

Large ponderosa pine veterans on dry sites, and grand fir on moist sites distinguish the ICHdw from the adjacent ICHmw2. Evidence from the age structure of three stands in the ICHdw suggests a mixed-severity disturbance regime in this subzone—frequent, low-severity fires maintained ponderosa pine on dry sites and higher-severity fires with longer return intervals permitted grand fir to establish on moister sites (Quesnel and Pinnell 2000). Evidence included a multi-aged stand with fire-scarred veterans and little mountain pine beetle activity, a similarly aged stand but with high beetle and root rot activity, and a stand with no veteran fire-scarred trees and a single pulse of establishment. Mean return intervals of low-severity fires in two ICHdw stands ranged from 11 to 24 years between 1762 and the 1890s—these rough estimates were determined from a small sample without crossdating. However, it is unknown how extensive these stand types are across the ICHdw landscape. Preliminary data of the age structure in the ICH in Wells Gray Provincial Park, ICHwk1 in

[9] Fire cycles were determined from a stand-origin map based on aerial photographs and field sampling.

the Upper Adams Valley, and the ICH in the Nelson Forest Region may support this complexity in disturbances regimes across the ICH (Arsenault 1997; Holt et al. 1999).

Pollack et al. (1997) used corrected Forest Inventory Planning (FIP) age-class data and estimated return intervals ranging from 101 years in the dry ICHdw, to 129 years in the ICHmw2, to 226 years in the wet ICHwk1.[10] In our analysis of the Arrow Forest District, reported in Part 3, we found a much wider range in pre-settlement disturbance return intervals. Depending on assumptions about pre-harvesting age of stands and predominant disturbance characteristics, we estimated return intervals of 65–449 years for the ICHdw and 97–458 years for the ICHmw2.[11]

Disturbance rates were highly variable in the past. In the ESSF and ICH, disturbance rates were lower in pre-settlement times relative to the early half of the 20th century. Disturbance rates were again lower in the later half of the 20th century. However, in the ICHmw2, where extensive logging has occurred, disturbance rates have increased. Current proportions of old forest are low for the ICHmw2 relative to the historic range. Both Pollack et al. (1997) and we assumed in our analyses that the disturbance regime is predominantly stand-replacing. However, data collected by Quesnel and Pinnell (2000) suggest instead that low- and mixed-severity disturbances may be predominant in certain parts of the ICH.

Disturbance severity varies both within and among the areas of recent mountain pine beetle outbreaks and fires in the ICH and ESSF in the Arrow TSA (McIntire 2001). Fires had two to three times higher median mortality than mountain pine beetle ($n = 14$ outbreaks and four fires) and the proportion of basal area killed by both agents increased along gradients from the edge of the disturbance perimeter. The size distribution of snags appears to vary substantially, although few large snags remain after mountain pine beetle outbreaks. Stuart-Smith and Hendry (1997) surveyed a fire that had burned in 1934 in the ICHmk1 and found residual clumps and islands within the fire perimeter. Arsenault (1997) found similar remnants inside fire boundaries in the ICH near Wells Gray.

Gap dynamics are another important component of forest dynamics in the ICH (Coates and Burton 1997). Gaps may be created by root rot and/or windthrow and, near the northern extent of the ICH, can make up to 6.6% of the area in ICHmc stands (Coates and Burton 1997). Most gaps were less than 150 m^2 but could reach up to 600 m^2. The variability in light regimes created by different gap sizes leads to different growth rates and other physiological responses in the species that regenerate in the gaps.

Over the province, outbreaks of western hemlock looper appear to be cyclic, occurring on average every 9 years (Parfett et al. 1995; Alfaro et al. 1999). Between 1911 and 1994, this insect has defoliated large areas of the ICHvk1, ICHvk2, ICHwk1, and ICHmw3 (Parfett et al. 1995). An outbreak in the Prince George Forest Region had high levels of tree mortality ranging from 51 to 96% of all trees dbh >7.5 cm after a 4-year outbreak beginning in 1992 (Alfaro et al. 1999). A study of 13 stands affected by at least 40% mortality from a western hemlock looper outbreak in the 1990s in Robson Valley found that the looper was not size or species specific but rather preferred trees with small live crown ratios (Hoggett 2000). Following looper outbreaks, a shift in canopy dominance from western hemlock to western redcedar is likely (Hoggett 2000). The probability of outbreaks, and their spread and severity for ICH and ESSF subzones in Robson Valley is described in Sutherland (2001).

Field-based Studies from Similar Ecosystems (United States, Alberta, Others) Mean fire intervals of stand-replacing fires, estimated for western redcedar forests in western Montana and northern Idaho, range from 57 to 500 years (reviewed in Pollack et al. 1997). Fires of mixed or low intensity occurred every 18–100 years in areas similar to the ICHdw and ICHmk1. In northern Idaho, fire scar evidence[12] indicates mean fire intervals of 50–150 years in small stands of western redcedar and hemlock (Arno and Davis 1980). Fires in upland western redcedar–hemlock burned with variable intensities, ranging from surface fires (some with very low severity, as cedar and larch survived) to crown fires. Fires were typically small: 0.1–120 ha, based on records between 1921 and 1978. See also Shiplett and Neuenschwander (1994) for a review of fire ecology of cedar–hemlock forests in northern Idaho.

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[10] Determined by fitting a negative exponential to corrected FIP data for error and for what ages stands were pre-harvest. A caveat of this method is that it is based on the average age of the codominant/dominant tree layer and implicitly assumes even-age stand dynamics. It is questionable whether this approach gives meaningful results for multi-cohort or all-aged stands typical of the drier subzones of the ICH and IDF.

[11] Determined by the Rollback Method (Method 1-C) on the basis of forest inventory age data. We accounted for expected error in FIP ages (see Part 3, this report). Note that the wide range in the estimates is partially a result of pooling results for several different scenarios; individual scenarios are listed in Table 1.

[12] Collected along 40 km of transects in each of two study areas ($n = 19$ trees each).

Technical comments

- Disturbance rates appear to have changed over the last century (Dorner and Lertzman 2001). Thus, it may be better to use the Rollback Method (Method 1-B or 1-C) in the ICH (see Parts 2 and 3, this report).

Interior Douglas-fir Zone

The Interior Douglas-fir zone (IDF) occurs at elevations between ~500 and 1500 m in south-central interior British Columbia (Tisdale and McLean 1957; Brayshaw 1970; Hope et al. 1991b). The climate is continental with a long, warm growing season characterized by substantial moisture deficits throughout the summer. Similar ecosystem types are found in the Interior west of the United States and in the Alberta Rocky Mountain Foothills. In the southern part of the IDF, lower elevations grade into the PP zone and higher elevations into the MS zone. Farther north, the BG zone forms the lower boundary, and either the SBPS or SBS zones form the upper boundaries. In a few areas of the Coast Mountains, the IDF occurs below the CWH zone (Hope et al. 1991b). The current version of British Columbia's BEC system differentiates nine IDF subzones with a total of 23 variants and phases.

In the IDF, fire, insect defoliators (e.g., western spruce budworm, Douglas-fir tussock moth), bark beetles, and root rot (Armillaria, laminated) are important natural agents of disturbance. In mountainous areas of the IDF, topography strongly influences local moisture regimes and the spread of disturbances, leading to structurally complex forest landscapes composed of multi-aged patches with ill-defined stand boundaries (Sandmann, unpubl.). The wetter and cooler plateau landscapes in the northern section of the IDF often consist of varying sizes of even-aged patches of lodgepole pine with scattered large veteran trees (Dawson 1998; Iverson et al. 2002).

The *Biodiversity Guidebook* gives 250 years as the mean interval between stand-replacing disturbances for NDT4 ecosystems (including all IDF subzones) and uses this figure to derive distributions of seral stages and patch sizes (B.C. Ministry of Forests and BC Environment 1995). The validity of this approach as well as the placement of all IDF subzones into this NDT have been questioned (Pollack et al. 1997; Lloyd 1999; Gayton 2001) and this has led to the establishment of an inter-agency NDT4 working group (A. Arsenault, B.C. Ministry of Forests, Forest Sciences, Kamloops, pers. comm., 2002). One task of this group is to review the research conducted in dry interior forests (Klenner et al. 2001).

Field-based Studies from British Columbia Specific to this Zone Many stands in the IDF show evidence of past fires such as fire scars on living or dead trees, charred logs, snags, or stumps, and soil charcoal. Throughout ecosystems associated with interior Douglas-fir, researchers have studied the historical frequency and variability of low- and mixed-severity fires, mostly by dendrochronological analyses of fire scars. The main attribute reported in these studies is the mean fire interval (MFI). However, it is often difficult to compare among studies, as the MFI might have been calculated for different time periods, with different sampling intensities, and for different study area sizes (see Measures of Disturbance Frequency, above; see also discussions by Fox 1989, and by Weisberg and Swanson 2001).

Many stands in the IDF contain fire-scarred trees which, because the fire intensity was not enough to kill the entire tree, indicate the importance of low-severity fires. The pre-European mean fire interval between these fires ranged from 5 to approximately 50 years in British Columbia. For the IDFxh2, Riccius (1998) estimated the range of point MFIs on six adjacent study sites in the lower Stein Valley to be 9–28 years. In elevational transects containing PPxh2, IDFxh2, IDFdk1, and MSxk in the Kamloops and Lillooet forest districts, MFIs ranged from 7 to 39 years. For one site in the IDFxm in the Churn Creek Protected Area, MFI was 14 years (Blackwell et al. 2001). For the IDFdm2 in the Rocky Mountain Trench, a point MFI of 14 and 19 years was estimated for two sites (Gray et al. 1998). In two elevational transects containing IDFdm2 and MSdk on south aspects, MFIs were 14 years in the Cranbrook Forest District and 18 years in the Invermere Forest District (Gray et al. 2002). For IDFdk2 sites in the mid–Stein Valley, Heyerdahl and Lertzman (unpubl.) estimated point MFIs over 38 stands to range between 15 and 47 years. Low-severity fires occurred on average every 13 years in IDFdk1 stands near Merritt (Gray and Riccius 1998), median of point MFIs from 5 to 49 years in

IDFdk3 stands in the Cariboo (44 stands [Iverson et al. 2002]; 9 stands [Daniels and Watson 2003]), every 5–44 years (area MFI: 15 yr) in IDFdk lodgepole pine stands of the central Chilcotin (not cross-dated [Douglas 2001]). For the IDFww forests near Pemberton, a range of point MFIs between 6 and 23 years was found (Gray and Riccius 2000). Point MFIs were approximately 50 years in forests similar to the IDFww in Desolation Peak, Washington, bordering Skagit Valley Provincial Park (Agee et al. 1990). Daigle (1996) contains a table with fire intervals and dates of last fires for seven sites throughout the dry interior forests; unfortunately, no further details are provided. Note that comparing studies is often difficult, as the MFI might have been calculated for different time periods, with different sampling intensities, and for different study area sizes.

Higher-severity disturbances are hypothesized to also have been historically important in parts of the IDF and influenced by vegetation type and local topography. Fire history studies that analyzed both fire scars and tree establishment dates indicate that fires of higher severity (or perhaps other stand-replacing disturbances) have occurred as well. In the Stein Valley, spatial co-occurrence of disturbances of varying severities has been observed in small and topographically distinct areas of less than 50 ha (IDFxh2 [Riccius 1998; Wong 1999]) as well as along landscape-scale gradients of several thousand hectares (IDFdk2 [Heyerdahl and Lertzman, unpubl.]). On the Cariboo Plateau IDFdk3, stands of pure Douglas-fir, mixed Douglas-fir / lodgepole pine, and pure lodgepole pine experienced the same frequency of low-severity fires, and, similar to the Stein Valley, were influenced primarily by low-severity fires (Iverson et al. 2002). However, in stands with lodgepole pine, evidence of patches of even-aged stand structure indicated that these stands did experience higher-severity events and thus could be characterized by mixed-severity fire regimes. Local changes in slope appeared to influence historic fire intensity and thus stand densities in the elevational transects sampled by Gray et al. (2002) in the IDF, but this finding was not tested statistically. The geographical extent of mixed-severity disturbance regimes in the IDF in British Columbia is unknown and is the subject of current debate. Inferences about disturbance severity in the IDF in the Kamloops Forest Region have been made based on old forest surveys (1910–1930s), fire, lightning, and fire weather index data since the 1950s (Klenner et al. 2001).

Pollack et al. (1997) applied statistical methods to the FIP inventory database to derive "natural age class" distributions and stand-replacement intervals. For the IDFdm variants occurring in the Nelson Forest Region, they conclude that the *Biodiversity Guidebook* figure (i.e., 250 yr) appears to overestimate stand-replacement intervals by a factor of two (see caveat of this method in the ICH [Pollack et al. 1997]).

The spatial extent (i.e., patch size) of historical low- or higher-severity fires is difficult to determine because patches are often not distinct enough to determine from air photos and analyses of fire scars and age cohorts face logistical limits. The few studies that estimated fire size distributions in IDF forest types found that most fires tended to be relatively small (<400 ha in Heyerdahl et al. 2001; <100 ha in Lertzman 2001). Low-severity fires in the lower Stein Valley seemed to be much smaller (2–4 ha), and are thought to be highly constrained by topographic fire breaks (Riccius 1998; Jordan 2002). In areas of the province where there are few topographic breaks, such as on the Cariboo Plateau, fires had the potential to be large (Iverson et al. 2002). The largest lightning-caused fire recorded during 1950–1998 in the Cariboo IDF was 1434 ha, and was likely suppressed (unpubl. B.C. Ministry of Forests fire database). In all studies, at least one fire year occurred that burned the entire study area, suggesting episodic severe fire weather events (see discussion in Agee 1997).

A dramatic decrease in fire frequency over the last century in the dry forest types, observed in all of the studies cited above, has led to an ongoing debate about causes and effects (e.g., Johnson and Wowchuk 1993; Gayton 1996; Arsenault and Klenner 2001). Decades-long fire-free periods before European settlement have been observed in most fire history studies but these tended to be local and generally not synchronized across regions (e.g., Gray et al. 2002) and may have been the result of the stochastic nature of fire ignition and spread (Lertzman et al. 1998). In the Cariboo IDFdk3, most current fire-free intervals exceed the historical maximum in sampled stands and coincide with European settlement (Iverson et al. 2002). Simulations of a pre-European fire regime on a pure Douglas-fir IDFdk3 landscape found most of the landscape burned repeatedly but a small proportion burned infrequently, such that the time since the last fire can be up to 250 years (Cumming and Wong 2002).

Modern tree encroachment into grasslands at the interface between the forest and grassland in the IDF of the Cariboo and Nelson forest regions, as recorded by comparing historic air photos with 1990s photos and examining patterns of tree establishment, coincide with modern fire exclusion and grazing (Strang and Parminter 1980; Gayton 1997; Ross 1997, 2000). In the BG and PP subzones in the South Okanagan and Lower Similkameen valleys, invasion and ingrowth of conifers into grasslands or open forest significantly increased in unburned sites when comparing 1938–1985 and 1985–1996 air photo pairs (Turner and Krannitz 2001). Encroachment in a meadow containing a disjunct ponderosa pine ecosystem in the upper Skagit Valley (IDFww) was linked to the absence of frequent First Nations fires and shallow spring snowpacks since the 1970s (Lepofsky et al. 2000). Gayton (1997) and Taylor and Baxter (1998) used repeat analysis of aerial photography and simulation modelling to quantify past changes and predict future trends in forest cover, fuels, and fire behaviour for two IDF/PP landscapes in the Rocky Mountain Trench, Kootenay River Valley, and Okanagan Valley.

Bark beetles, insect defoliators, and root diseases have significant impacts on stand and landscape dynamics in the IDF (e.g., Alfaro et al. 1984, 1987; Alfaro 1986; Heath and Alfaro 1990; van der Kamp 1991; Maclauchlan and Brooks 1994; Sturrock and Garbutt 1994; Davis and Machmer 1998; Miller and Maclauchlan 1998). The area disturbed by insects and diseases can exceed that disturbed by wildfire over different periods of time but actual tree mortality can vary with the nature of the particular insect or disease (Parminter 1998). Compiling baseline data on pre-European dynamics of forest insects and pathogens and their interactions with wildfires is challenging because site-specific data about historical outbreak intervals, severities, and extents are difficult to reconstruct.[13] Instead, most research projects are concerned with predicting future outbreaks and the impact of management actions on these (e.g., Alfaro and Maclauchlan 1992; Shepherd 1994; Negron 1998).

For most of the 20th century, data on insect epidemics have been collected and published by provincial and federal ministries (e.g., Erickson 1987; Wood and Unger 1996). To date, only a few studies have tried to analyze the temporal dynamics of specific disturbance agents in these spatial data. Harris et al. (1985a, 1985b) describe historical outbreaks of Douglas-fir tussock moth and western false hemlock looper, respectively. The authors do not provide quantitative information; instead, each report summarizes the historical data in a three-class "risk map" of potential future infestations. Currently, staff at the Pacific Forestry Centre in Victoria are transferring all available maps of fires, insects, and diseases into a digital atlas and database (G. Dalrymple, Canadian Forest Service, Pacific Forestry Centre, pers. comm., 2002). Within the limits of data quality and resolution, this product will supply a much better basis for spatio-temporal analyses of historical disturbance dynamics.

Field-based Studies from Similar Ecosystems (United States, Alberta, Others) Useful examples of an integrated approach to the assessment of ecosystem change compared with historical baseline information in dry forests are the Interior Columbia Basin Ecosystem Management Project (ICBEMP) and its predecessor, the Eastside Forest Ecosystem Health Assessment.[14] Reports of particular interest relating to disturbance attributes are Fischer and Bradley (1987), Agee (1994), Morgan et al. (1996), Barrett et al. (1997), Hessburg et al. (1999), Everett et al. (2000), McKenzie et al. (2000), Hemstrom (2001), Quigley et al. (2001), and Thies (2001). Some of the information in these reports might be directly applicable to similar ecosystems in British Columbia. However, the data, methods, and assumptions presented in each source document should be carefully examined.

Simulation Modelling of Natural Disturbances Klenner et al. (2000) used computer simulations to assess the influence of wildfire and harvesting regimes on seral-stage distributions and patch size characteristics, specifically for old-growth reserves. Based on a comparison of several hypothesized scenarios, the authors concluded that the current practice of dispersed cutblocks, combined with stochastic fire events, is unlikely to maintain patch size distributions and old-growth targets as specified in the *Biodiversity Guidebook* (Klenner et al. 2000).

Researchers at the Pacific Forestry Centre extended the U.S. Forest Service's fire effects and successional model (FVS FFDEM) with a landscape-level module calibrated for several IDF and PP subzones (Taylor and Baxter 1998). Based on input data collected in four study areas in the Kamloops and Nelson forest regions, model projections of 50 years into the future predict that the area of grassland and open forests will continue to decrease in some locations. If these changes do occur, they will significantly affect fire behaviour potential, landscape diversity, and other aspects of forest management.

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[13] Anderson et al. (1987) analyzed radial increment cores to estimate historical changes in outbreak frequency, intensity, and duration of western spruce budworm in western Montana.

[14] Most ICBEMP reports and databases are available from http://www.icbemp.gov/html/.

Technical comments

- Interpretation of stand dynamics, such as the relative role of low- and higher-intensity fires, insects, and pathogens in the IDF requires careful integration of both past stand structure and fire history data.
- Standard dendrochronological methods exist for dating fire scars, including crossdating to master chronologies to obtain annual accuracy of fires and determining a "period of reliability" with sufficient replication to confidently reconstruct fire regimes (e.g., Dieterich 1980; Grissino-Mayer 1995).

Mountain Hemlock Zone

The Mountain Hemlock zone is the subalpine zone above the CWH in the mountains along the coast of British Columbia. It is found at 900–1800 m in elevation in the south, and 400–1000 m in the north (Pojar et al. 1991b). The MH is characterized by cool, short summers and long, wet, cool winters; mean monthly temperatures are above 10°C for only 1–3 months and mean annual precipitation can be 1700–5000 mm. The current version of British Columbia's BEC system differentiates three MH subzones with a total of 10 variants and phases (B.C. Ministry of Forests 2001). Disturbances are primarily fires, landslides, avalanches, and wildlife browsing. The *Biodiversity Guidebook* designates the MH subzones as NDT1, with rare, stand-initiating events of mean return intervals of 350 years, and MH parkland as NDT5. The vegetation and environmental relationships in the MH have been described in Brooke et al. (1970) and Klinka and Chourmouzis (2001).

Field-based Studies from British Columbia Specific to this Zone Forest fires in the MH occur infrequently—intervals between stand-replacing events can be centuries to millennia (Lertzman 1992; Lertzman et al. 2002; Hallett et al. 2003). This variability is thought to be linked to climatic patterns. An 11 000-year fire history, reconstructed from charcoal in soil and lake sediment in the subalpine in the Fraser Valley, found periods of relatively frequent fire during the early Holocene (10 000–8000 years ago) and other periods when climate was warm and dry (Hallett et al. 2003). Mean fire intervals over the entire soil charcoal record were 555 ±100 years (±1 standard deviation error) for a site in the Coast Mountains, and 455 ±190 years for another site in the North Cascades (Hallet et al. 2003). Mean fire intervals estimated from charcoal in lakes draining basins near these sites were approximately 300 years shorter.

Because of the long return intervals, stands tend to be multi-aged, and tree age is an unreliable indicator of stand age. Fine-scale processes, causing the death of one to a few trees and creating gaps in the canopy, tend to dominate forest dynamics in the MH in similar ways as in the CWH. In the MH forest on the Lower Mainland, 18% of the forest area was in developmental canopy gaps (Lertzman and Krebs 1991). Stem snap of canopy dominants infected with stem rot was the principal mode of gap formation (Lertzman and Krebs 1991; Lertzman et al. 1996). Gaps, as measured to the boles of trees forming the canopy gap boundaries, ranged from 0.0025 to 0.11 ha (Lertzman and Krebs 1991). For gaps in MH forests on the Lower Mainland, turnover rates (i.e., the average length of time between successive disturbances at one location within a stand) range from 556 to 1111 years (Lertzman and Krebs 1991).[13] Edaphic gaps, related to topography or soil, were found to be important in the MH in Clayoquot Sound (Lertzman et al. 1996). However, regeneration in the MH parklands close to the AT zone is more influenced by tree islands, elevated microsites in association with snowpack duration and depth, than by gap dynamics (Brett and Klinka 1998; Klinka and Chourmouzis 2001).

Field-based Studies from Similar Ecosystems (United States, Alberta, Others) Some work described in the AT and CWH zones may be applicable to the MH.

Simulation Modelling of Natural Disturbances Temporal modelling of species composition in the MH under varying climate found that composition and coexistence of shade-intolerant species was maintained by species having different mortality rates and climate-dependent fluctuations (Lertzman 1995).

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[13] Estimates of successive disturbance rates depend on the time estimated to fill a gap. In this study, 100–200 years were assumed.

Technical comments

- Fire history is difficult to reconstruct in the MH, as there are few fire-scarred trees and even-aged stands. Radiocarbon dating inherently contains inaccuracies in resulting fire dates depending on the age of the wood at the time it burned (Gavin 2001). Because of the intensive analysis required to date charcoal, charcoal records tend to be temporally rich but, if based on soil samples, cover only a small area, and, if extracted from lake sediments, cover an ill-defined area within the lake catchment.
- Note that comparing MFI from paleoecological data between different sites is appropriate when they were derived from point sources (small catchments or different points for soil record) or when the area of the catchment is known.

Montane Spruce Zone

The Montane Spruce zone (MS) occupies mid-elevation slopes and plateaus in the mountains of the dry southern interior of British Columbia. It occurs as an elevational band of 300–400 m above the IDF or SBPS and below the ESSF (Hope et al. 1991c). The MS has a cool, continental climate transitional between that of the IDF and ESSF, with mean annual precipitation between 380 and 900 mm. While the MS has strong floristic affiliations with both the ESSF and the IDF, it is distinguished from these by its extensive seral stands of lodgepole pine. The current version of British Columbia's BEC system differentiates seven MS subzones with a total of nine variants (B.C. Ministry of Forests 2001).

Stand-replacing wildfires and severe mountain pine beetle outbreaks are the two main agents that maintain forests of lodgepole pine in various successional stages across MS landscapes. Pine-to-pine replacement after bark beetle outbreaks depends on overstorey mortality and site conditions (Stuart et al. 1989; Fuchs 1999). Partial disturbances by low-severity fires, bark beetles, fungal pathogens, and dwarf mistletoes open the canopy and allow the establishment of shade-tolerant spruce and fir (Lloyd et al. 1990). The *Biodiversity Guidebook* designates all MS subzones as NDT3, with frequent stand-initiating events at approximately 150-year intervals (B.C. Ministry of Forests and BC Environment 1995).

Field-based Studies from British Columbia Specific to this Zone Probably due to the MS's limited geographical extent in British Columbia, few projects have established research sites exclusively within the zone. Masters (1990) used stand-age maps to infer fire frequency and its variability over time for the MSdk and ESSFdk in Kootenay National Park. The resulting time-since-fire distribution suggested three periods of different fire frequency, reported as fire cycles for the park area: 1508–1788 (60 yr), 1888–1928 (130 yr), and 1928–1988 (>2700 yr). This extreme fire cycle is hypothesized to be the result of moist weather, not of effective fire suppression. Unfortunately, the author did not analyze the two biogeoclimatic zones in the study area separately.

Reed (1994) used the MS zone in the Kootenay TSA (likely the MSdk) as an example for determining the historical probability of stand-replacing fires from the age-class distribution. The result based on the Maximum Likelihood Estimate (see Method 1-B, Part 2, this report) was 51 years with a 95% confidence interval of 35–101 years (Reed 1994).

An analysis of charcoal and pollen in sediments of Dog Lake in Kootenay National Park provided a 10 000-year record in changes of vegetation types and fire frequency in the lake's vicinity (Hallett and Walker 2000). The authors conclude that the long-term range of natural variability for climate and fire in the Kootenay Valley was very broad, with lake-basin forest types ranging from dry, open IDF to closed, wet ESSF. Variability in climate is inferred from changes in the pollen record (i.e., pollen ratios of tree species) and variability in charcoal accumulation in the lake sediment. Current conditions are intermediate in this range (i.e., MSdk). Inferred fire frequency varied continuously throughout the Holocene (last 11 000 yr) and for the last ~500 years ranged from 200 to 250 years. This number is much larger than the 60- to 130-year fire cycle for Kootenay National Park reported by Masters (1990) and is probably a result of the limited temporal resolution of charcoal records.[16]

Pollack et al. (1997) used corrected forest inventory age data and statistical techniques to estimate stand-replacement intervals for a number of BEC variants in the Nelson Forest Region. For the MSdk, their modelling scenarios estimate replacement intervals of 108–124 years and for the MSdm1, 107–123 years.

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[16] Hallett and Walker (2000) actually used Master's stand-age maps to calibrate their statistical analyses of the charcoal accumulation record before computing the inferred fire frequency.

Aspect and neighbouring fire regimes appear to influence the severity of fire regime dominant in MS stands. In elevational transects including IDFdm2 and MSdk in the Cranbrook Forest District, MSdm1 in the Invermere Forest District, and IDFxh2, IDFdk1, and MSxk in the Kamloops Forest District, south aspects were characterized by frequent, mixed-severity fire regimes of point MFIs of 14–39 years (Gray et al. 2002). Similar transects on north aspects showed little evidence of fire-scarred trees and most stands had multi-cohorts or were even-aged, indicating a mixed- to high-severity fire regime.

The influence of aspect on disturbance regime is supported by Holt et al. (2001), who sampled 38 MSdk stands in the Nelson Forest Region to develop old-growth definitions based on structural attributes. While the study does not directly address the role of natural disturbances, it provides qualitative evidence for differences in disturbance regimes within this subzone. Wet stands developed large trees and snags with increasing age in a relatively predictable manner, suggesting few post-establishment disturbances. In contrast, dry stands exhibited a wide variety of structural attributes independent of age, suggesting a strong influence of mixed-severity disturbances. In the western larch–lodgepole pine forests of the west side of Montana's Glacier National Park, Barrett et al. (1991) also found a mixed-severity fire regime closely correlated with local climate and topography.

Several of the studies cited in our literature review for the IDF and ESSF collected data in MS stands as well. Stuart-Smith and Hendry (1998) examined residual trees and patches in five fires that had burnt partially or entirely within the MSdk subzone of the Nelson Forest Region. They found that residual patches varied greatly in size (2–55 ha) and total fire area covered by residual trees ranged from 0.6 to 25% (fires ranged from 245 to 2909 ha). Larger tree islands sometimes contained spruce and fir but most of the smaller patches and all individual wildfire survivors were either Douglas-fir or western larch (Stuart-Smith and Hendry 1998).

Empirical data of the frequency and extent of mountain pine beetle outbreaks or other insect pathogens are available as annual overflight maps (e.g., Erickson 1987) but remain to be analyzed for the MS. Wood and Unger (1996) summarized some of these maps by timber supply area but did not subdivide their analyses by BEC zone. Periods between outbreak peaks ranged between 13 and 60 years, while individual epidemics extended over 5–8 years (Wood and Unger 1996). Fuchs (1999) and Drever and Hughes (2001) recently reviewed the literature about mountain pine beetle research.

Field-based Studies from Similar Ecosystems (United States, Alberta, Others) For the Lower Subalpine Zone of Jasper National Park, Andison (2000) used an age-class Rollback Method (see Part 2, this report) to estimate historical rates of burning and their changes over time. Between 1791 and 1930, fires burned on average ~13% (5–32%) of the forest in a 20-year period. In the three 20-year periods between 1931 and 1990, these values have been reduced to between 0.2 and 0.7% (Andison 2000).

Johnson and Fryer (1989) examined the population dynamics of 13 lodgepole pine–Engelmann spruce stands in the MS-like forests of the Kananaskis Valley, Alberta. Their data provide evidence for long-term coexistence of both species across the landscape, even though lodgepole pine is considered early successional. The authors suggest that coexistence is facilitated due to the average fire return interval being shorter than the lifespan of lodgepole pine: less than 2% of the stands in the Kananaskis survive to 300 years (Johnson and Fryer 1989).

In the western larch–lodgepole pine forests of the west side of Montana's Glacier National Park, Barrett et al. (1991) found a mixed-severity fire regime closely correlated with local climate and topography. On drier MS sites, low-severity fires (MFI, 24–76 yr) occurred in addition to high-severity fires (MFI, 107–243 yr). On wetter sites, few of the larches had fire scars, suggesting a primarily stand-replacing fire regime with an MFI of 202 years (range: 131–332 yr).

Kipfmueller and Baker (1998) studied the degree of infection of lodgepole pine by dwarf mistletoe in relation to stand-replacing fire (*n* = 34 stands; southeastern Wyoming). In general, mistletoe infection increased with increasing time-since-fire but was highly variable. At the landscape scale, infection rates appeared to be directly correlated with distance to "infection centres" (i.e., highly infected stands [Kipfmueller and Baker 1998]).

Stuart et al. (1989) examined fire history, mountain pine beetle epidemics, and regeneration requirements in an old-growth lodgepole pine stand in south-central Oregon. The multi-aged structure of the forest was attributed to episodic mid-severity disturbances and subsequent gap-phase pine regeneration pulses. Competition for soil moisture rather than canopy shading limited seedling survival (Stuart et al. 1989).

Fischer and Bradley (1987) present a comprehensive analysis of interactions between lodgepole pine, wildfire, and mountain pine beetle. They compiled available data and literature and propose successional models both for conditions under which lodgepole pine is a seral species and where it is persistent (Fischer and Bradley 1987, pp. 46–49). Agee (1994) contains a recent summary of research on fire and extreme weather disturbances in the U.S. dry interior.

Simulation Modelling of Natural Disturbances
None known.

Technical comments

- Barrett et al. (1997) discuss with insight a major impediment to quantifying fire extents in mixed-severity fire regimes: the legacy of infrequent, extensive high-severity fires that remove most of the evidence of previous fires.
- Disturbance frequencies based on stand-origin data or charcoal deposits assume that fire is the only agent responsible for stand-replacing events. In areas susceptible to severe insect outbreaks, such as lodgepole pine–dominated stands in the MS, this assumption may not hold. Consequently, stand-replacement intervals based on stand-origin maps are not necessarily *fire* intervals, and charcoal records may underestimate overall disturbance frequencies because they are unable to detect insect outbreaks (e.g., Masters 1990 vs. Hallett and Walker 2000).
- The observation that disturbance rates have varied over time suggests that age distributions are not in equilibrium in these forests. Consequently, Methods 1-B or 1-C (see Part 2, this report) should be the methods of choice.

Ponderosa Pine Zone

The Ponderosa Pine zone (PP) stretches between 49° and 51° N along dry valleys in the southern Interior Plateau of British Columbia (Hope et al. 1991a). It is typically found between 330 and 900 m, above the BG and below the IDF zones. The PP is the driest (mean annual precipitation is 280–500 mm) and, during summer, the warmest forested zone in the province. The current version of British Columbia's BEC system differentiates two PP subzones with a total of six variants and phases (B.C. Ministry of Forests 2001).

Given its spatial proximity to the BG and/or the IDF, the PP is characterized by similar low- to mid-severity fire regimes. Other disturbance agents important in creating canopy gaps include drought, mountain pine beetle, Douglas-fir beetle, Douglas-fir moth, Armillaria, tomentosus, *Phellinus weirii*, dwarf mistletoe, stem rusts, and *Elytroderma deformans* and *Lophodermella* spp. needle casts (Lundquist and Negron 2000; Wong 2001). The *Biodiversity Guidebook* designates the two PP subzones as NDT4, with frequent, stand-maintaining events of mean return intervals of 4–50 years.

Field-based Studies from British Columbia Specific to this Zone Mean fire intervals of low-severity fires ranged from 9 to 28 years in a small study area of 28 ha transitioning the PPxh and IDFxh in the Kamloops Forest Region (mean = 17 yr) (Riccius 1998). The size of these fires was estimated to be small, mostly 2–4 ha, as the area was a series of river terraces highly constrained by topography. However, low-severity fire regimes were not predominant on every terrace—evidence of higher-severity disturbances, derived from the patterns of tree establishment, was found on some of the terraces (Wong 1999). Point mean fire interval of an elevational transect in the PPxh near Spences Bridge was 7 years (Gray et al. 2002). Other fire history studies in the PP zone in British Columbia each found mean fire intervals of less than 10 years (e.g., Dorey 1979; Low 1988; Cartwright 1983, cited by Parminter 1990). These studies likely underestimated fire intervals because they did not follow standard dendrochronological methods when dating fire events, such as crossdating.

The role of higher-severity fires in ponderosa pine forests is unclear and is subject to much debate in British Columbia and elsewhere (e.g., Shinneman and Baker 1997; Baker and Ehle 2001; Klenner et al. 2001). Inferences about disturbance severity in the PP zone are based on old forest surveys (e.g., 1910–1930s), fire, and lightning and fire weather index (since the 1950s) for the NDT4 in the Kamloops Forest Region. Readers are referred to Klenner et al. (2001) for more details. Analyses of these records clearly show that harvesting in the PP in the Kamloops Forest Region peaked in the 1960s, that fires have prevailed, and that insect defoliators appear to be increasing since the 1950s (Klenner et al. 2001).

In the BG and PP of the South Okanagan and Lower Similkameen valleys, invasion and ingrowth of conifers into grasslands or open forest significantly increased in unburned sites (Turner and Krannitz 2001).[17] Sites that did burn decreased in conifer density, and conifer establishment did not differ between latitude or biogeoclimatic zone for unburned sites. Using a similar method, Gayton (1997) concluded that in the PP in the Rocky Mountain Trench, open grassland, treed grassland, and corresponding forage nutrition has decreased by 0.76%/yr since 1952.

Little is known about the distribution of dead and remnant living trees following low-severity fires. Two fires in 1940 and 1960, in the PPdh in the East Kootenays, had remnant veteran Douglas-fir and ponderosa pine as single trees (20–33 trees/100 ha), clumps (averaging 1.8 ha and 4.3 trees/100 ha), and islands (averaging 6.8 ha and 0.4 trees/100 ha) (Stuart-Smith and Hendry 1998).

Field-based Studies from Similar Ecosystems (United States, Alberta, Others) Substantial research has characterized historic fire regimes in ponderosa pine forests in the United States (see review of 36 studies in Baker and Ehle 2001). Mean return intervals, as determined from fire scars pre-European settlement, ranged from 2 to 107 years. Fires in these forests were patchy: 10–58% of the area within a fire perimeter was unburned (Baker and Ehle 2001). The observation that many fire history studies, based on fire-scarred trees, ignore years-to-first-fire scar as a fire interval and do not incorporate age structure into their analyses, has been criticized as biasing results towards shorter mean fire intervals (Baker and Ehle 2001). However, it is questionable whether years-to-first-fire scar is a valid fire interval because of uncertainty in the length of regeneration delays. If regeneration delays are longer than expected fire intervals, years-to-first-fire scar are an inaccurate estimate of interval.

Simulation Modelling of Natural Disturbances Taylor and Baxter (1998) simulated fire regimes for two interior British Columbia landscapes (PPdh2 and IDFdm2; PPxh1 and IDFxh1) and projected changes in classes of forest crown closure.

Technical comments

- See comments under IDF zone.

Sub-Boreal Pine–Spruce Zone

The Sub-Boreal Pine–Spruce zone (SBPS) occurs south and west of the SBS in central interior British Columbia, in the shadow of the Coast Mountains (Steen and Demarchi 1991). The SBPS is found at elevations above the IDF and below the MS, SBS, and ESSF (typically between 850 and 1500 m). The climate of the SBPS is continental and, compared with the SBS and BWBS, drier, with fewer growing degree days >5°C. The current version of British Columbia's BEC system differentiates four SBPS subzones only (B.C. Ministry of Forests 2001).

The forests of the SBPS are thought to be dominated by mixed- and high-severity disturbances, primarily fire, which create patches of even-aged forest further modified throughout time by stand-maintaining disturbances. However, increasing evidence of fire-scarred lodgepole pine (Vera 2000; Francis et al. 2002) suggests that low-severity fires may have been more important than previously thought. Mountain pine beetle and spruce beetle can also kill host species at the landscape level in the SBPS. Within stands, the Douglas-fir bark beetle and Armillaria and tomentosus root rots can cause mortality. Disturbance agents that primarily reduce tree growth include the forest tent caterpillar, lodgepole pine dwarf mistletoe, terminal and root collar weevils, adelgids, and stem rusts (Wong 2001). The *Biodiversity Guidebook* designates all of the SPBS subzones as NDT3, with frequent, stand-initiating events of mean return intervals of 100 years.

Field-based Studies from British Columbia Specific to this Zone The SBPSxc and SBPSdc on the Chilcotin Plateau are dominated by a mixed-severity fire regime: many frequent small to medium fires punctuated every 40–100 years by extremely large fires (Francis et al. 2002). The years 1869 and 1922 were extremely large fire years and also very dry years in both the SBPS and the IDFdk3 in the Cariboo area, indicating that regional climate can drive episodic fire events across large areas (possibly up to 1 million ha) in this landscape (Francis et al. 2002; Iverson et al. 2002). Large fires like these violate the assumptions of traditional analyses based on time-since-fire distributions (Johnson and Gutsell 1994). However, fire cycles of mixed- to high-intensity fires calculated using field data and air photo interpretation to reconstruct individual fires were similar to mean fire return intervals determined from fire scars (1831–present: SBPSxc, 45 ±26 yr; SBPSdc, 64 ±40 yr, mean ±1 standard deviation [Francis et al. 2002]; see also uncrossdated estimate for SBPSxc in Douglas 2001). Annual disturbance rates were approximately 2.0%/yr for various time periods (1869–1961) and

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[17] Based on analyses of aerial photography of the same sites taken in 1938, 1985, and 1996.

decreased to 0.01%/yr between 1961 and 2001.

In the wetter subzones, fires appear to be less frequent. Francis et al. (2002) found a fire cycle of 170 years between 1922 and 1961 in an area containing SBPSmk, SBSdw1, and SBSdw2 in the Cariboo area. The disturbance cycle of stand-replacing disturbances in the SBPSmc in the Lakes and Morice TSAs was estimated as 91 years for the period 1800–1970 (Steventon 2001).[18]

In the SBPS on the Chilcotin Plateau, mixed- to high-intensity fires span a range of sizes, most of which are small (SBPSxc mean = 1557 ha, median =141 ha; SBPSdc mean = 1369 ha, median = 33 ha), although much of the landscape was influenced by very large events (approximately 70 000 ha) at some point (Francis et al. 2002). The drier xc subzone appeared to have more frequent fires, larger fires on average, and more area with overlapping fires (Francis et al. 2002). In the SBPSmk, average fire sizes were smaller (325 ±1490 ha). However, they were determined from a time-since-fire map (1700s–2001), and are therefore biased towards smaller patch sizes because the map was not adjusted for overlapping fires (Francis et al. 2002). In the Lakes and Morice TSAs, >40% of the current SBPS landscape is in patches >500 ha (Steventon 2001).

The mixed-severity fire regime in the SBPSxc and SBPSdc on the Chilcotin Plateau is composed of high-severity fires (45% of the 20 000 ha burned by four fires since 1905 had <15% of the original stand survive) and mixed- to low-severity fires (20% of the area burned had 16–40% remnant forest and 32% of the area had >41% remnant forest) (Francis et al. 2002). Severity varies across subzone—the SBPSdc had more area influenced by higher-severity fires than the SBPSxc. Fires typically burn through these remnants but at a lower intensity (Vera 2000). Evidence of this is found in multiple fire-scarred trees in remnant patches of nine fires that burned in the early 1900s in the SBPSxc (Vera 2000). Remnant patches are small, averaging 20–34 ha, but form 3–11% of the total area burned (Francis et al. 2002).

Interactions between fires and mountain pine beetle likely drive forest dynamics in lodgepole pine stands extensive in the SBPS. Records of multiple fires and mountain pine beetle attacks since 1850 were found in four SBPSxc stands in the Chilcotin using dendrochronological analyses of fire- and beetle-scarred trees. Most stands experienced two low-severity fires followed by one or two mountain pine beetle attacks. The mountain pine beetle outbreak in the Chilcotin in the 1980s caused up to 31% mortality of lodgepole pine trees (T. Shore, B. Hawkes, and S. Taylor, Canadian Forest Service, Pacific Forestry Centre, Victoria, B.C., unpubl. data). Provincial records of mountain pine beetle outbreaks extend back to 1910 but in general do not span sufficient numbers of outbreaks to determine the variability in return intervals. However, many forest regions have experienced two or three outbreaks since 1910 (Wood and Unger 1996), suggesting that mountain pine beetle outbreaks can occur on a landscape at less than 100-year intervals. It is unknown how often spruce beetle outbreaks occur in the SBPS but this is likely similar to the SBS.

Wind disturbance in the SBPS have not been characterized. However, critical wind speeds causing endemic and stand-replacing windthrow, while highly specific to landscape position and stand and soil characteristics, are thought to be ≥50 km/h (Sinton et al. 2000). Return intervals for winds double this critical speed are approximately 26–40 years near Williams Lake and Quesnel as projected from weather station records (Murphy and Jackson 1997).

Field-based Studies from Similar Ecosystems (United States, Alberta, Others) Studies conducted in the SBS and MS in British Columbia may also be relevant.

Simulation Modelling of Natural Disturbances None known.

Technical comments

- The observation that disturbance rates have varied over time in different SBPS subzones suggests that age distributions are not in equilibrium in these forests. Consequently, Methods 1-B or 1-C (see Part 2, this report) should be used for stand-replacing events.
- Using the proportion of area in a certain age class to determine disturbance rates or patch size distributions is appropriate only where disturbance intervals are very long, such as in the SBSvk (e.g., Hawkes et al. 1997); where the analysis has been restricted to age classes not likely to have been logged, originated from suppressed fires, or reburned by subsequent fires (e.g., DeLong 1998); or where reburns by subsequent fires have been mod-

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[18] Determined using forest inventory age classes 3–7 with no correction for reburns in older age classes.

elled or sampled in the field (e.g., Andison 1996).

Sub-Boreal Spruce Zone

The Sub-Boreal Spruce zone (SBS) dominates the landscape of central interior British Columbia between 51°30'N and 59°N, at 1100–1300 m in elevation (Meidinger et al. 1991). The SBS adjoins the BWBS in the north, the ICH in the wet areas to the northeast and east, the IDF and SBPS in the south, and the ESSF at higher elevations. The climate is continental; average temperatures are below 0°C for 4–5 months of the year and mean annual precipitation is between 440 and 900 mm, of which up to 50% can be snow. Seral species are lodgepole pine and aspen; climax species are subalpine fir, and white spruce and Engelmann spruce hybrids. The current version of British Columbia's BEC system differentiates 11 SBS subzones with a total of 20 variants and phases (B.C. Ministry of Forests 2001).

Fires of mixed to high intensity dominate the natural disturbance regimes of most SBS forests (Parminter 1992). Widespread and high-severity windthrow and mountain pine and spruce bark beetle outbreaks are also influential. Other stand-replacing disturbances, which are more site-specific, include avalanches, ice storms, and floods. Even-aged patches are modified by stand-maintaining disturbances in the absence of further stand-replacing disturbances (Lewis and Lindgren 2000). Young seedlings can be attacked by black army cutworm, and saplings by terminal and root-collar weevils. As trees mature, cankers, stem rusts, needle diseases, and lodgepole pine dwarf mistletoe typically reduce growth in groups of trees but rarely cause widespread mortality. Patchy mortality within mature stands can be caused by Armillaria and tomentosus root rots, Douglas-fir bark beetle attacking Douglas-fir on dry sites, and western balsam bark beetle attacking subalpine fir at mid-elevations. Defoliators, such as the 2-year-cycle budworm, western blackheaded budworm, western hemlock looper, and forest tent caterpillar, are important and frequent events. The *Biodiversity Guidebook* designates most SBS subzones as NDT3, with frequent, stand-initiating events of mean return intervals of 125 years, and the wet and very wet subzones (wk, vk) as NDT2, with mean return intervals of 200 years.

Field-based Studies from British Columbia Specific to this Zone Stand-replacing disturbances (assumed to be primarily fire) appear to vary across the SBS subzones, following a gradient in precipitation (DeLong 1998). Mean annual precipitation during spring to fall accounted for 91% of the variation in the mean fire cycle (DeLong 1998). In the montane ecosystems, the fire cycle during 1910–1950 ranged from 244 years in the moist subzone (SBSmk1), to 500 years in the wet subzone (SBSwk1), to 1666 years in the very wet subzones (SBSvk). In SBS subzones on plateaus, the fire cycle was lowest for those with intermediate levels of precipitation (SBSmk1 and SBSmc3), ranging from 104 to 270 years (DeLong 1998).[19] For the approximately same time period (1922–1961), Francis et al. (2002) found a fire cycle of 170 years in an area containing SBSdw1, SBSdw2, and SBPSmk in the Williams Lake and 100 Mile House forest districts. These disturbance intervals may not reflect historic intervals but lie within the range of values reported by other studies for longer time periods.

Other estimates of fire cycles are 100 years for the SBSdk, 125 years for the SBSmc in the Lakes and Morice TSA (Steventon 2001),[20] and from 80 to 100 years for the entire SBSmk1 (Andison 1996).[21] In the very wet and cool SBSvk on the McGregor Plateau, mean return intervals are estimated to be much longer, ranging from 1205 to 6250 years (Hawkes et al. 1997).[22] Between 1850 and 1950, fire has disturbed 0.35–1.2% of the SBSmk1 landscape annually (Andison 1996; DeLong and Tanner 1996). These estimates do not take into account the additional amount reburned by subsequent fires. Andison (1996) estimates that accounting for reburns would increase the estimate to approximately 2%. During 1970–1990, fire disturbed 0.15% of the total SBSmk1 landscape, whereas harvesting disturbed 12%. Harvesting is replacing fire as the dominant disturbance process in these forests (DeLong and Tanner 1996).

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[19] These intervals were determined using forest inventory age classes 3 and 4 (41–80 yr) to avoid uncertainty in stand origin (natural fires vs. logging or suppressed fires) and uncertainty in area in older age classes that may have reburned in subsequent fires (DeLong 1998).

[20] Determined using forest inventory age classes 3–7, with no correction for reburns in older age classes.

[21] Determined using forest inventory, fieldwork to divide age class 8 into 20-year age classes, and the Rollback Method (see Part 2, this report) to account for reburning of older age classes (Andison 1996).

[22] The results represent disturbances rates based on the proportion of area in age classes 3–7 (41–140 yr). Age classes 1 and 2 were avoided because of uncertainty in stand origin (natural fire vs. suppressed fire or logging). Age class 8 was avoided because of inaccurate ages. However, because 90% of the McGregor landscape fell in age class 8, it follows that there are relatively long return intervals between disturbances in the SBSvk.

Regional precipitation patterns and topography influence disturbance size—in montane topography average patch size decreased along a moisture gradient across SBS subzones, and patch size distributions were significantly different between the mk1, wk1, and vk (DeLong 1998). On plateaus, the largest patches (mean, maximum, and standard deviation) were found in subzones with intermediate levels of precipitation (mk and mc). Although large disturbances dominate the sub-boreal landscape, most patches are small. In the SBSvk on the McGregor Plateau, 53% of the examined patches were <10 ha and <1% were >1000 ha (Hawkes et al. 1997). Patch sizes for the Cariboo SBSdw1 and SBSdw2 are estimated by Francis et al. (2002) to average ~300 ha ± ~1000 ha (1 standard deviation) but were not adjusted for subsequent overlapping fires and likely underestimate average patch size.

Fires in the SBS can be patchy in severity—fires in the 1930–1950s left 1–73 ha of remnant forest covering 3–15% of the burned area (SBSmk1) (DeLong and Tanner 1996). Seven selected fires, which burned in the SBSmc and ESSFmc or ESSFdk in the Lakes/Morice TSA, left 1–245 ha of remnant forest as determined from air photos (Cliff Manning Forestry Services 2001). Since 1950, fires have been less variable in size (DeLong and Tanner 1996). The structure of these fire refugia differs from the adjacent mature forest by having larger trees, snags, and uneven-aged lodgepole pine regeneration not typically found in the SBS (DeLong and Kessler 2000).

Dendrochronological analysis of growth-release patterns of subalpine fir in the SBS suggests that high-severity outbreaks of spruce beetle occurred every 40–100 years in the McGregor Model Forest (Zhang et al. 1999). The patterns of release were found over 10 sites within 165 000 ha, suggesting that widespread, high-severity outbreaks occurred infrequently. Between 1963 and 1986, the size of spruce beetle outbreaks ranged from tens of hectares to 26 000 ha in the Cariboo area (Andrews 1986). Other high-severity disturbances documented in the SBS include wind and mountain pine beetle. As with the SBPS, their historical disturbance regimes have not been quantified for the SBS.

Without stand-replacing disturbances, gap disturbances drive stand dynamics in the SBS (Kneeshaw and Burton 1997). Reconstruction of stand development in 14 old stands in the SBSmc2 found several possible trajectories after stand-replacing fires. Some of the stands had all species in stand initiation—a period that can last from 50 to over 100 years; others had subalpine fir as a late-successional species only. Spruce was recruited early in stand development and maintained itself by re-establishing in gaps created by single-tree disturbances caused by bark beetles, root rot, and windthrow.

Other more widespread low- to mixed-severity disturbances include flooding and defoliators. Along the Morice River, 31 flood events were recorded over 105 years by scars in trees (Gottesfeld and Johnson-Gottesfeld 1990). This finding suggests that in the SBS, flooding of sufficient severity to scar trees and presumably cause some mortality can occur relatively frequently. Outbreaks of 2-year-cycle budworm in the Fort St. James and Mackenzie forest districts occurred approximately every 30 years over the past 100 years, each event lasting about 10 years (Zhang and Alfaro 2002). Outbreaks can cause 16–20% reduction in radial growth each year of the outbreak; outbreak intensity appears greatest in moist/wet and cool/cold variants of the SBS and ESSF (Shand et al. 1999). Western hemlock looper will defoliate white spruce, particularly in the wet subzones (SBSmc, mm, vk, wk1). Between 1911 and 1994, western hemlock looper has defoliated a total of 17 500 ha in the SBS (Parfett et al. 1995). Outbreaks of forest tent caterpillar can range from a group of aspen to the 190 000 ha defoliated in 1990 in the Northern Interior Forest Region (Ferris 1994).

Field-based Studies from Similar Ecosystems (United States, Alberta, Others) Some of the research in the boreal forests may be applicable to the sub-boreal.

Simulation Modelling of Natural Disturbances Andison (1996) models stand-replacing fire events across the SBSmk1 to compare landscape pattern generated by fire with that generated by forest management.

Technical comments

- Only a few studies cited above used fieldwork to determine stand origin dates or dates of fire events (Andison 1996; Francis et al. 2002).
- The observation that disturbance rates have varied over time in different SBS subzones suggests that age distributions are not in equilibrium in these forests. Consequently, Methods 1-B or 1-C (see

- Part 2, this report) should be the methods of choice.
- Characterizing the variation in disturbance rates over time is challenging, due to the erasure of evidence by reburning of the older age classes.
- The size of remnant forest may be underestimated because small patches are generally not recorded in forest cover inventories (Andison 1996).
- Using the proportion of area in a certain age class to determine disturbance rates or patch size distributions is appropriate only where disturbance intervals are very long, such as in the SBSvk (e.g., Hawkes et al. 1997), or where the analysis has been restricted to age classes not likely to have been logged, originated from suppressed fires, or reburned by subsequent fires (e.g., DeLong 1998), or where reburns by subsequent fires have been modelled or sampled in the field (e.g., Andison 1996).

Spruce–Willow–Birch Zone

The Spruce–Willow–Birch zone (SWB) is the most northerly subalpine zone in British Columbia, extending from 56°30'N to 70°N in Yukon and Northwest Territories (Pojar and Stewart 1991b). The SWB lies above the BWBS at 1000–1700 m in elevation in the north and 900–1500 m in the south. Winters are long and cold and summers short and cool; temperatures average >10°C for 1 month only, and mean annual precipitation is 460–700 mm. Lower elevations of the SWB are generally forested with white spruce and trembling aspen. At higher elevations, subalpine fir dominates, giving way to shrubs where the growing season becomes too short. Early seral stands of lodgepole pine are uncommon. It appears that fires are less frequent than in the adjacent BWBS (Pojar and Stewart 1991b). Early succession after fire is usually dominated by shrubs and aspen (Parminter 1983b). The composition of further stand development depends on the fire severity, initial stand composition, and seed-bearing capability of surviving conifers (Parminter 1983b). Fires often burn at mixed intensities due to the discontinuities in fuels common in these stands. Stands are typically multi-aged, given the relatively long intervals between fires (Parminter 1983b). The *Biodiversity Guidebook* describes the disturbance regime in all four subzones as NDT2, with a mean return interval of 200 years for stand-replacing events.

Field-based Studies from British Columbia Specific to this Zone Spatially explicit modelling of fires was used to estimate historical fire cycles in the Mackenzie TSA while accounting for overlapping fires (Rogeau 2001; see discussion in the BWBS review and Table 2). While the SWB was not analyzed separately, most fires were <1000 ha, although these accounted for only 5–18% of the area burned, as determined from the B.C. Ministry of Forests fire database from 1942 to 1991 (Rogeau 2001).

Field-based Studies from Similar Ecosystems (United States, Alberta, Others) None known.

Simulation Modelling of Natural Disturbances None known.

1.5 Assessment of Knowledge Gaps

The preceding literature review of natural disturbances in British Columbia may give the impression that this field of research is well developed. However, Table 1, which lists available quantitative information by BEC variant, leads to a less encouraging conclusion. Disturbance intervals have been characterized for 45% of the 91 biogeoclimatic subzones (excluding parkland and undifferentiated subzones in the ESSF) (Figure 1). For most of British Columbia's 190 biogeoclimatic variants, little or no empirical data exist on disturbance attributes. The Alpine Tundra and Coastal Douglas-fir zones have received no formal study, perhaps due to either particular methodological challenges or the small geographical extent of the CDF in British Columbia.

Several zones in Figure 1, particularly the ESSF, SBPS, and SBS, have had more research than average. However, most subzones in these zones are described by only one study, which is likely insufficient to represent their entire range of environmental conditions. In some cases, such as in the ICHmw, IDFdk, and CWHvm, more than three studies have been conducted in different geographic locations within the same subzone.

Remember that the quality of the data and methods varies among the studies; consequently, the estimates of disturbance intervals also vary. For example, all four subzones in the SBPS appear to be well researched, but two of the studies used unconventional methods (see SBPS review). In addition, differences in results based on different assumptions are sometimes greater than differences between subzones.

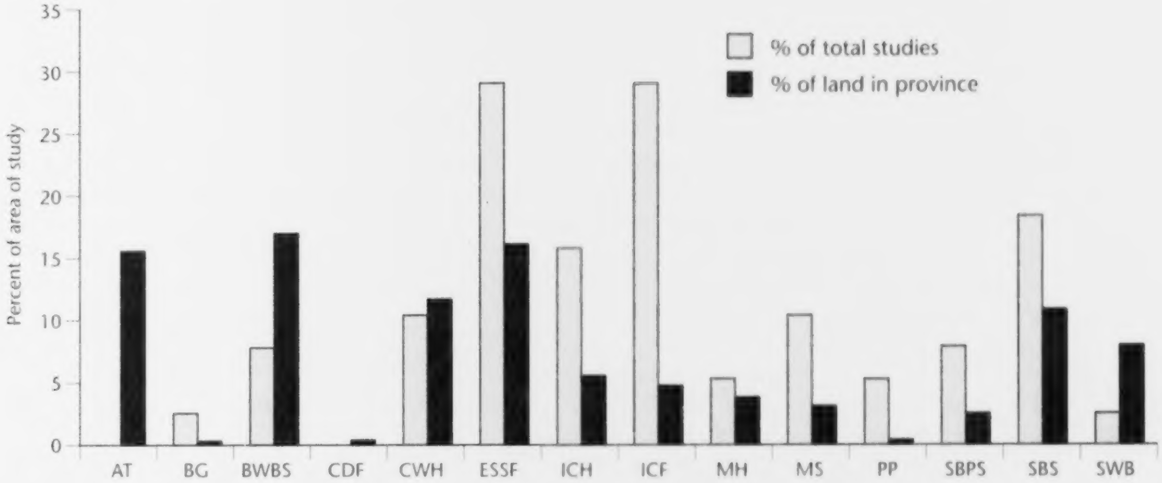

FIGURE 1 *Distribution of 38 studies on disturbance intervals across British Columbia's biogeoclimatic zones (BEC data from M. Eng, B.C. Ministry of Forests, Research Branch).*

The terms of reference for this project required us to focus on return intervals of disturbances. However, we also considered disturbance intensity/severity and size as extremely important characteristics of disturbance regimes and included in our review any studies in British Columbia that described these characteristics. Most of the studies focused on stand-replacing fires—few agents other than fire were described (Figure 2). Figure 2 illustrates how poorly other attributes of disturbances other than frequency have been described in British Columbia. For example, only one-quarter of the 91 subzones have descriptions of the size of disturbance patches and only six subzones have adequate descriptions of the distribution of the size of remnants within disturbance perimeters. Note that the composition and structure of remnants has received more research (e.g., DeLong and Tanner 1996; Stuart-Smith and Hendry 1998; DeLong and Kessler 2000; Vera 2000). Thus, where attributes have been quantified, they tend to lack spatial coverage and temporal depth.

Obviously, our knowledge about the historic variability in natural disturbance dynamics in British Columbia is incomplete. Below, we identify and summarize what we believe to be the most crucial gaps in knowledge and methods:

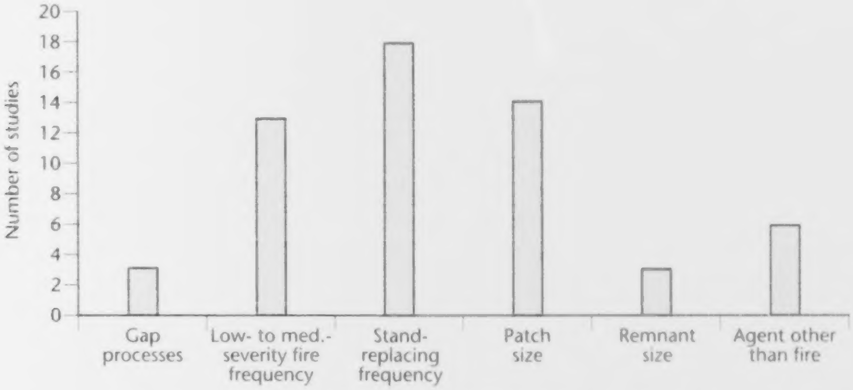

FIGURE 2 *Distribution of 41 studies in British Columbia that have determined return intervals for different levels of disturbance severity and the size of disturbance patches and remnants. Most of the studies on stand-replacing events assumed the agent to be fire. Geomorphic disturbances are not included.*

- The spatial "resolution" of the historical variability in natural disturbances is likely smaller than the biogeoclimatic variant and often associated with site-specific topographic conditions. Yet the research conducted in British Columbia to date covers less than half of the biogeoclimatic subzones and therefore captures only a small amount of the overall ecological and topographic variation in the province.
- Not all of the 190 variants have distinct disturbance types; however, there does not appear to be a consistent method for pooling variants. Substantial research exists in similar ecosystems outside of British Columbia, but differences in the biogeoclimatic classification used in British Columbia and other vegetation classifications used in Alberta, the Yukon, and the United States made it difficult for us to extrapolate data from other areas to the appropriate biogeoclimatic subzone.
- Several research projects pooled data across their entire study area, despite obvious ecological dissimilarities (e.g., two or more BEC subzones or zones).
- Few studies have been subject to formal peer review.
- Many methodological challenges are involved in describing the historic variability in disturbances in British Columbia. For example, few studies were able to adequately address the influence of human activities on the landscape or to obtain sufficient temporal and spatial depth in field sampling.
- Temporal and ecological interactions of two or more disturbance agents may influence forest succession in much more profound ways than either agent in isolation. Yet few projects have tried to quantify cumulative or interacting effects between different agents.
- The impacts of past, present, and future human activities—such as logging, fire suppression, and livestock grazing—on disturbance regimes and future climate change are not well understood.

We do not want to discredit the many past and present research projects studying the natural dynamics of British Columbia's ecosystems; in fact, we were impressed by the number of published and unpublished reports that we accumulated in our survey. Nevertheless, the substantial lack of quantitative information made obvious in this review leads us to conclude that the state of knowledge about natural disturbances in British Columbia remains limited. We believe that these gaps in knowledge are due to the incredible diversity of British Columbia's ecosystems and the limited resources directed to disturbance research. In Part 4 of this report, we summarize these gaps and provide recommendations about how to close them.

TABLE 1 *Database of research on disturbance frequency and patch characteristics of various disturbance agents in biogeoclimatic subzones in British Columbia. Geomorphic disturbances are not included. We strongly recommend that users refer directly to the primary research.*

Zone	Subzone	Guidebook mean return interval (yr)	Author	Location	Method	Period of record	Disturbance agent	Range in disturbance rates	Mean disturbance rate
AT		NDT 3	none known						
BG	xh	NDT 4	Blackwell et al. (2002)	Churn Creek Protected Area (xh3)	dendrochronological dating of fire scars (n = one 10-ha site, 7 trees)	1706–2000	low-severity fires		
BG	xw	NDT 4	none known						
BWBS	?	100–125	Shore and Alfaro (1986)	near Liard	dendrochronological dating of ring patterns in host and non-host species	1869–1980s	eastern spruce budworm		
BWBS	?	100–125	Burleigh et al. (2002)	Fort Nelson Forest District	dendrochronological dating of ring patterns in host and non-host species	1817–1992	eastern spruce budworm		
BWBS	dk	100–125	Rogeau (2001)	Mackenzie TSA 873 112 ha – 1 549 306 ha (4 different terrain units)	• spatially explicit modelling of historic fires in different terrain units (see comment) • also air photo interpretation of 1950s set and analyses of MOF fire database	~1860	stand-replacing events	0.31–1.49%/yr	0.32–1.33%/yr
BWBS	dk	100–125	DeLong (1998)	633 381 ha near Prince George (dk1)	analysis of forest inventory, using age classes 3 and 4	1911–1950	stand-replacing events	0.22–0.38%/yr	0.3%/yr
BWBS	dk	100–125	Francis et al (1999) as reported by Reid (2003)	Blue River/Liard Basin (dk1, dk2, some SWB)	unknown	1730–2000	stand-replacing events		0.138–0.468%/yr
BWBS	mw	100–125	none known but see comment	•					
BWBS	un		none known						
BWBS	vk	100–125	none known						
BWBS	wk	100–125	none known						
CDF	mm	200	none known						
CWH	dm	200	none known						
CWH	ds	200	none known but see Gray et al. (2002) and IDFww						
CWH	mm	200	none known						
CWH	ms	200	none known						

Range fire cycle / Mean return interval (yr)	Mean fire cycle / Mean return interval (yr)	Range in time since fire	Mean time since fire	Patch size	Remnant size	Comments	Zone	Subzone
							AT	
3–81	19						BG	xh
							BG	xw
14–28							BWBS	?
	26					• outbreaks in northern sites began about 10 years earlier and lasted longer than in southern sites • length of defoliation periods 6–17 years, based on two outbreaks (1950s and 1980s)	BWBS	?
60–390	75 (±8; 1 SD) to 303 (±18)			1950 air photos: 1880 ± 2717 ha (average ± 1 SD) 4423 ± 7799 ha depending on region		• since details on verification and calibration of the model used (STANDOR) are not provided, results should be interpreted with care • 4 units had some proportion of BWBS, SWB, and SBS • historic regimes simulated using probability of ignitions based on lightning ignitions in MOF database >1950	BWBS	dk
333				• 23% of disturbed area in 1910–1950 in patches > 1000 ha • 19% < 100 ha		used age classes 3 and 4 to avoid effects of fire suppression, harvesting, reburns	BWBS	dk
314–733				180–3900 ha (mean)		NOTE that we were unable to obtain a copy of the report in time to critically review methods, etc.	BWBS	dk
						Alfaro et al. (2001) (mw2) found 1.5–6%/yr of spruce mortality during eastern spruce budworm outbreak	BWBS	mw
							BWBS	un
							BWBS	vk
							BWBS	wk
							CDF	mm
							CWH	dm
							CWH	ds
							CWH	mm
							CWH	ms

TABLE 1 *Continued*

Zone	Subzone	Guidebook mean return interval (yr)	Author	Location	Method	Period of record	Disturbance agent	Range in disturbance rates	Mean disturbance rate
CWH	un		none known						
CWH	vh	250	re-analysis of Mitchell (1998) by Dorner and Wong (2002) (see also Pearson 2003)	North Coast TSA (55% vh2, 18% vm)	air photo interpretation of 62 blowdown patches in operable area	1960–1996	wind		0.03%/yr
CWH	vm	250	Gavin (2000); see also Lertzman et al. (2002)	700 ha in Clayoquot Valley (vm1)	method 1: point estimates from tree establishment dates and radiocarbon dates on soil charcoal (83 sites along grid)	tree dates AD 1550–1886; radiocarbon dates 280–10330 [illegible]	fire		
CWH	vm	250	Gavin (2000)	110 ha around 1 lake in Clayoquot Valley (vm1)	method 2: charcoal concentration in sediment	AD 200–present	fire		
CWH	vm	250	Green et al. (1999)	Capilano watershed (vm1, vm2)	dating establishment of old cohorts of Douglas-fir along transects in 17 selected sites, *n* = 306 trees (crossdated)	AD 797–1964	fire		
CWH	vm	250	Lertzman et al. (1996)	Tofino Creek, Clayoquot (vm1)	measured canopy gap in 43 plots along transects in stands in 3 developmental stages		gap processes		
CWH	vm	250	Lertzman et al. (1996)	Tofino Creek, Clayoquot (vm2)	measured canopy gap in plots in 7 plots		gap processes		
CWH	wm	250	none known						
CWH	ws	200	none known						
CWH	xm	200	none known						
ESSF	xc and/or dc	150	Parish and Antos (2002)	Damfino Creek, Okanagan Highlands	dendrochronological analysis of growth suppression relative to non-host species	1690–1990	2-year cycle budworm		
ESSF	xv	200	none known						
ESSF	dc	150	Pollack et al. (1997)	Nelson Forest Region (dc1)	fitted age classes; negative exponential		stand-replacing events		
ESSF	dk	150	van Wagner (1995) based on Masters (1990)	Kootenay National Park	regression and graphical analysis (neg. exponential) of age-class distribution		stand-replacing fire		
ESSF	dk	150	Pollack et al. (1997)	Nelson Forest Region	fitted age classes; negative exponential		stand-replacing events		
ESSF	dk	150	Rogeau (1996)	Mt. Assiniboine Prov. Park	time-since-fire distribution based on stand-origin map		stand-replacing fire		
ESSF	dk	150	Masters (1990)	Kootenay National Park	time-since-fire distribution based on stand-origin map	1508–1928	stand-replacing fire		

Range fire cycle / Mean return interval (yr)	Mean fire cycle / Mean return interval (yr)	Range in time-since-fire	Mean time-since-fire	Patch size	Remnant size	Comments	Zone	Subzone
							CWH	un
3000 (if assume landscape equally susceptible, see text)				1–118 ha, average 11 ha		notes large episodic event 150 years ago	CWH	vh
		64–12 000 BP	hillslopes = median 750; terraces = median 4500	rarely extended beyond 250 m in diameter		• time-since-fire varied significantly with topography • did not sample higher elevations where fires could spread • see also Pearson (2000), Jakob (2000) for geomorphic disturbance frequency	CWH	vm
50 (AD 200–900); 350 (AD 1100– present)						spatial pattern of fire around lake not random	CWH	vm
200–450*	345	33–1200 BP				* from dated multi-cohorts in 7 stands • primarily focused on areas with fire evidence (e.g., Douglas-fir cohort, charcoal); 49% of area did not have this evidence and could have burned in the past with evidence later erased	CWH	vm
345–1379**				5.0 ± 2.9 gapmakers/gap (mean ± SD)		** depending on time to fill gap; see text	CWH	vm
313–1250**				3.7 ± 2.2 gapmakers/gap (mean ± SD)		** depending on time to fill gap; see text	CWH	vm
							CWH	wh
							CWH	ws
							CWH	xm
30–46	45					• 4 plots in one stand • length of reduced-growth periods 2–22 yr	ESSF	xc and/or dc
							ESSF	xv
	149						ESSF	dc
	110						ESSF	dk
	138						ESSF	dk
	220					author considered this an inappropriate method as spatial homogeneity assumption violated	ESSF	dk
	60 (in 1508–1788); 150 (in 1788–1928)					study area combines MSdk and ESSFdk	ESSF	dk

TABLE 1 *Continued*

Zone	Subzone	Guidebook mean return interval (yr)	Author	Location	Method	Period of record	Disturbance agent	Range in disturbance rates	Mean disturbance rate
ESSF	dk	150	Stuart-Smith and Hendry (1998)	Invermere Forest District	air photo interpretation of post-fire trees and patches	1938–1967	mixed-severity fires		
ESSF	dv	150	none known						
ESSF	mw	200	see Gray et al. (2002) IDFww						
ESSF	mw	200	Stuart-Smith and Hendry (1998)	Invermere Forest District	air photo interpretation of post-fire trees and patches	1934	mixed-severity fires		
ESSF	mm	200	none known						
ESSF	mk	200	Steventon (2001)	Lakes/Morice TSA, Prince Rupert Region	forest inventory, negative exponential, truncated	1800–1970	stand-replacing events	0.01–0.07%/10 yr (80% CI)	
ESSF	mc	200	Zhang and Alfaro (2002); Zhang et al. (2001) (includes mv)	sites in Prince George, Robson Valley, Mackenzie, and Fort St. James forest districts	dendrochronological analysis of growth suppression relative to non-host species	1880s–2000	2-year cycle budworm		
ESSF	mc	200	Steventon (2001)	Lakes/Morice TSA, Prince Rupert Region	forest inventory, negative exponential, truncated	1800–1970	stand-replacing events	0.04–0.06%/10 yr (80% CI)	
ESSF	mv	200	DeLong (1998)	280 416 ha near Prince George (mv1)	forest inventory, proportion in age classes 3 and 4	1911–1950	stand-replacing events	0.19–0.48%/yr	0.34%
ESSF	wm	350	Pollack et al. (1997)	Nelson Forest Region	fitted age classes; negative exponential		stand-replacing events		
ESSF	wk	350	Hawkes et al. (1997)	121 000 ha near McGregor Model Forest (wk2)	forest inventory, proportion in age classes 3–7	1850–1950	stand-replacing events	0.071–0.188%/yr	0.14%
ESSF	wc	350	Pollack et al. (1997)	Nelson Forest Region (wc4)	fitted age classes; negative exponential		stand-replacing events		
ESSF	wc	350	Dorner et al. (2001)	Arrow Forest District (wc1)	rollback method using FIP data	1700–1860	1) small frequent disturbances 2) episodic large events 3) episodic large age-dependent events		
ESSF	wc	350	Dorner et al. (2001)	Arrow Forest District (wc4)	rollback method using FIP data	1700–1860	1) small frequent disturbances 2) episodic large events 3) episodic large age-dependent events		

Range fire cycle / Mean return interval (yr)	Mean fire cycle / Mean return interval (yr)	Range in time-since-fire	Mean time-since-fire	Patch size	Remnant size	Comments	Zone	Subzone
				87–1728 ha	2–26 ha	6 fires; see also ESSFmw and MSdk	ESSF	dk
							ESSF	dv
							ESSF	mw
				2909 ha	4–100 ha	1 fire only; see also ESSFdk and MSdk	ESSF	mw
							ESSF	mm
	689						ESSF	mk
24–39	32					• outbreaks synchronized between forest districts but size and intensity varied • length of reduced-growth periods 7–11 yr	ESSF	mc
	219						ESSF	mc
	294			61% of landscape in patches >1000 ha		used age classes 3 and 4 to avoid effects of fire suppression, harvesting, reburns	ESSF	mv
	153						ESSF	wm
532–1429	794			23% of landscape in patches >1000 ha		includes ESSFwk2 and SBSvk	ESSF	wk
170							ESSF	wc
1) 28–3598[1] 2) 39–3218 3) 52–6471	1) 90 / 237[2] 2) 112 / 247 3) 174 / 535					1 min/max numbers reflect the 95% confidence interval in time-since-disturbance estimates, derived from 100 runs of a stochastic model. The three scenarios reflect different assumptions about disturbance dynamics. 2 the left value is the mean interval assuming equal hazard of logging; the right value assumes logging targeted old stands.	ESSF	wc
1) 23–2459[1] 2) 35–2385 3) 47–6765	1) 92 / 173[2] 2) 104 / 184 3) 183 / 326					1 min/max numbers reflect the 95% confidence interval in time-since-disturbance estimates, derived from 100 runs of a stochastic model. The three scenarios reflect different assumptions about disturbance dynamics. 2 the left value is the mean interval assuming equal hazard of logging; the right value assumes logging targeted old stands.	ESSF	wc

TABLE 1 *Continued*

Zone	Subzone	Guidebook mean return interval (yr)	Author	Location	Method	Period of record	Disturbance agent	Range in disturbance rates	Mean disturbance rate
ESSF	wc	350	Dorner et al. (2001)	Arrow Forest District (wcp4)	rollback method using FIP data	1700–1860	1) small frequent disturbances 2) episodic large events 3) episodic large age-dependent events		
ESSF	wv	350	Steventon (2001)	Lakes/Morice TSA, Prince Rupert Region	forest inventory, negative exponential, truncated	1800–1970	stand-replacing events	0.01–0.03%/10 yr (80% CI)	
ESSF	vc	350	Pollack et al. (1997)	Nelson Forest Region	fitted age classes; negative exponential		stand-replacing events		
ESSF	vc	350	Rogeau (2000)	greater area around Mt. Revelstoke National Park (93 754 ha)	field sampling and landscape modelling of historic fires in different valley orientations		stand-replacing fire		
ESSF	vv	350	none known						
ICH	dk	150	none known						
ICH	dw	150	Quesnel and Pinnell (2000)	West Arm Demonstration Forest, Kootenay Lake	dated fire scars ($n = 7$ trees, not crossdated) age structure in 4–5 plots in 3 stands	1762–1890	low-severity fires		
ICH	dw	150	Pollack et al. (1997)	Nelson Forest Region	fitted age classes; negative exponential		stand-replacing events		
ICH	dw	150	Dorner et al. (2001)	Arrow Forest District (dw)	rollback method using FIP data	1700–1860	1) small frequent disturbances 2) episodic large events 3) episodic large age-dependent events		
ICH	mc	200	Coates and Burton (1997)	Date Creek, north of Hazelton	measured canopy gap along transects in 16 different site and age units		gap processes		
ICH	mk	150–200	Pollack et al. (1997)	Nelson Forest Region (mk1)	fitted age classes; negative exponential		stand-replacing events		
ICH	mm	200	none known						
ICH	mw	150–200	Pollack et al. (1997)	Nelson Forest Region (mw2)	fitted age classes; negative exponential		stand-replacing events		

Range fire cycle / Mean return interval (yr)	Mean fire cycle / Mean return interval (yr)	Range in time-since-fire	Mean time-since-fire	Patch size	Remnant size	Comments	Zone	Subzone
1) 24–7132† 2) 35–5919 3) 34 – >10 000	1) 92 / 173‡ 2) 103 / 184 3) 138 / 326					† min/max numbers reflect the 95% confidence interval in time-since disturbance estimates, derived from 100 runs of a stochastic model. The three scenarios reflect different assumptions about disturbance dynamics. ‡ the left value is the mean interval assuming equal hazard of logging; the right value assumes logging targeted old stands.	ESSF	wc
	566						ESSF	wv
	222						ESSF	vc
110–180	145 ± 15			34–59% < 10 ha 1–2.5% > 1000 ha average = 100 ha (depending on season)		• since calibration and verification of model were not provided, results should be interpreted with care • MFRI from field data in park alone ranged from 18 to 48 years • size classes of fires not separated by BEC subzone and include ICHwk	ESSF	vc
							ESSF	vv
							ICH	dk
	stand 1 (midslope): 11.1 (*n* = 3 scarred trees) stand 2 (upperslope): 24.4 (*n* = 4 trees)					• suggest that age structure indicates higher-severity fires too • found difference in incidence of mountain pine beetle, root rot between 3 stands	ICH	dw
	101						ICH	dw
1) 13 – >10 000† 2) 25 – 9652 3) 42 – >10 000	1) 45 / 215‡ 2) 64 / 227 3) 125 / 932					† min/max numbers reflect the 95% confidence interval in time-since-disturbance estimates, derived from 100 runs of a stochastic model. The three scenarios reflect different assumptions about disturbance dynamics. ‡ the left value is the mean interval assuming equal hazard of logging; the right value assumes logging targeted old stands.	ICH	dw
				most are < 150 m² max = 600 m²		6.6% area in gaps	ICH	mc
	101						ICH	mk
							ICH	mm
	129						ICH	mw

TABLE 1 *Continued*

Zone	Subzone	Guidebook mean return *interval (yr)*	*Author*	*Location*	*Method*	Period of record	Disturbance agent	Range in disturbance rates	Mean disturbance rate
ICH	mw	150–200	Gavin prelim. results (mw2)		paleoecological record of charcoal in lake sediment				
ICH	mw	150–200	Dorner et al. (2001)	Arrow Forest District (mw2)	rollback method using FIP data	1700–1860	1) small frequent disturbances 2) episodic large events 3) episodic large age-dependent events		
ICH	un		none known						
ICH	vc	250	none known						
ICH	vk	250	Dorner et al. (2001)	Arrow Forest District	rollback method using FIP data	1700–1860	1) small frequent disturbances 2) episodic large events 3) episodic large age-dependent events		
ICH	wc	200	none known						
ICH	wk	250	Pollack et al. (1997)	Nelson Forest Region (wk1)	fitted age classes; negative exponential		stand-replacing events		
ICH	wk	250	Johnson et al. (1990) (wk1)	Glacier National Park	time-since-fire distribution from stand-origin map developed from field sampling	1519–1988	stand-replacing fire		
ICH	wk	250	Rogeau (2000)	greater area around Mt. Revelstoke National Park (93,734 ha)	field sampling and landscape modelling of historic fires in different valley orientations		stand-replacing fire		
ICH	wk	250	Dorner et al. (2001)	Arrow Forest District (vk1)	rollback method using FIP data	1700–1860	1) small frequent disturbances 2) episodic large events 3) episodic large age-dependent events		

Range fire cycle / Mean return interval (yr)	Mean fire cycle / Mean return interval (yr)	Range in time-since-fire	Mean time-since-fire	Patch size	Remnant size	Comments	Zone	Subzone
intervals of 200 yr in a row; also 300–800 intervals+K107						includes ESSFwc4	ICH	mw
1) 33–3598[1] 2) 44–3218 3) 66 – >10 000	1) 81 / 237[2] 2) 94 / 289 3) 161 / 788					[1] min/max numbers reflect the 95% confidence interval in time-since-disturbance estimates, derived from 100 runs of a stochastic model. The three scenarios reflect different assumptions about disturbance dynamics. [2] the left value is the mean interval assuming equal hazard of logging; the right value assumes logging targeted old stands.	ICH	mw
							ICH	un
							ICH	vc
1) 19 – >10 000[1] 2) 32 – >10 000 3) 34 – >10 000	1) 133 / 334[2] 2) 151 / 401 3) 207 / 472					[1] min/max numbers reflect the 95% confidence interval in time-since-disturbance estimates, derived from 100 runs of a stochastic model. The three scenarios reflect different assumptions about disturbance dynamics. [2] the left value is the mean interval assuming equal hazard of logging; the right value assumes logging targeted old stands.	ICH	vk
							ICH	wc
	226					see also Hoggett (2000) (Hw longer)	ICH	wk
	80 (1519–1760) 110 (>1760)					• includes the ESSF • periods of change were determined *a posteriori* from changes in slope in the time-since-fire distributions. See Huggard and Arsenault (1999, 2001) and Reed and Johnson (1999) for a critique and debate of this method.	ICH	wk
130–240	181 ± 19			34–59% < 10 ha 1–2.5% > 1000 ha average = 100 ha (depending on season)		• since calibration and verification of model were not provided, results should be interpreted with care • MFRI from field data in park alone ranged from 18 to 48 years • size classes of fires not separated by BEC subzone and include ESSFvc	ICH	wk
1) 24 – >10 000[1] 2) 56 – >10 000 3) 40 – >10 000	1) 133 / 225[2] 2) 149 / 256 3) 209 / 418					[1] min/max numbers reflect the 95% confidence interval in time-since-disturbance estimates, derived from 100 runs of a stochastic model. The three scenarios reflect different assumptions about disturbance dynamics. [2] the left value is the mean interval assuming equal hazard of logging; the right value assumes logging targeted old stands.	ICH	wk

TABLE 1 *Continued*

Zone	Subzone	Guidebook mean return interval (yr)	Author	Location	Method	Period of record	Disturbance agent	Range in disturbance rates	Mean disturbance rate
ICH	xw	250	none known						
IDF	dk	stand-maintaining 4–50, stand-replacing 250	Gray and Riccius (1999)	Pothole Creek Research Site, near Merritt (dk1)	dendrochronological analysis of fire scars on 23 trees and snags (crossdated)	1693–1967	low-severity fires		
IDF	dk	stand-maintaining 4–50, stand-replacing 250	Heyerdahl unpubl.	mid–Stein Valley (dk2 and un)	dendrochronological analysis of fire scars on 107 trees (crossdated)	1700–1996	low-severity fires		
IDF	dk	stand-maintaining 4–50, stand-replacing 250	Douglas (2001)	Cariboo Region (dk3, 4)	n = 23 trees, 11 stands (not crossdated)	1839–1989	low-severity fires		
IDF	dk	stand-maintaining 4–50, stand-replacing 250	see Gray et al. (2002) MSdk	dk1					
IDF	dk	stand-maintaining 4–50, stand-replacing 250	Iverson et al. (2002)	Cariboo Region (Williams Lake to Clinton; dk3)	dendrochronological dating of fire scars (265 samples) and increment cores (crossdated) of 44 stands	1750–2000	low-severity fires		
IDF	dk	stand-maintaining 4–50, stand-replacing 250	Daniels and Watson (2003)	Cariboo Region (Williams Lake to Clinton; dk3)	dendrochronological dating of fire scars (136 samples) and increment cores (crossdated) of 9 stands	1575–1988 (uncensored)	low-severity fires		
IDF	dm	stand-maintaining 4–50, stand-replacing 250	Gray et al. (1999)	2 sites Rocky Mountain Trench (dm2)	dendrochronological analysis of 7–9 trees/site (crossdated) increment cores from all trees > 20 dbh in 50*50 m plots	1694–1883 1683–1894	low-severity fires		
IDF	dm	stand-maintaining 4–50, stand-replacing 250	see Gray et al. (2002) MSdk, MSdm	dm2					
IDF	dm	stand-maintaining 4–50, stand-replacing 250	Pollack et al. (1997)	Nelson Region (dm1 and dm2)	mean stand age of inventory age classes, fitted against negative exponential model		stand-replacing events		
IDF	dw	stand-maintaining 4–50, stand-replacing 250	none known						
IDF	mw	stand-maintaining 4–50, stand-replacing 250	none known						
IDF	un		none known						

Range fire cycle / Mean return interval (yr)	Mean fire cycle / Mean return interval (yr)	Range in time-since-fire	Mean time-since-fire	Patch size	Remnant size	Comments	Zone	Subzone
							ICH	xw
	13		1967 (low severity)			maximum fire interval 46 yr (Q78 between 1788 and 1834	IDF	dk
15–47 for 38 sampled stands	21		1968 (low severity)			return intervals for low- to mid-severity fires only	IDF	dk
5–44	15						IDF	dk
							IDF	dk
	median of point MFI : 5–49 across plots: 22					• sites randomly selected from existing growth and yield plots within strata • no significant difference in frequency across pure low-elevation Fd, mixed Fd-Pl, and pure Pl high elevation strata • mixed-severity in mixed Fd-Pl and pure Pl	IDF	dk
2–59	median of point MFI: 13–22					• sites subjectively selected • also estimated fire intervals from dates recorded on ≥ 2 trees • age structure evidence of mixed severity fire regime • fire occurrence linked to droughts and onset of strong La Nina events	IDF	dk
	19 and 14		1883, 1894				IDF	dm
							IDF	dm
	121 (dm1) 111 (dm2)					study used mean stand age, not age of oldest trees	IDF	dm
							IDF	dw
							IDF	mw
							IDF	un

TABLE 1 *Continued*

Zone	Subzone	Guidebook mean return interval (yr)	Author	Location	Method	Period of record	Disturbance agent	Range in disturbance rates	Mean disturbance rate
IDF	ww	stand-maintaining 4–50, stand-replacing 250	Gray et al. (2002)	Haylmore Creek, Squamish Forest District	dendrochronological analysis of 8–11 fire-scarred trees (crossdated) and increment cores in 2 elevational transects	1555–2001	low-severity fires		
IDF	ww	stand-maintaining 4–50, stand-replacing 250	Gray and Riccius (2000)	5 watersheds near Pemberton	dendrochronological analysis of 3–9 trees/5–9 ha in each of 5 watersheds (crossdated); increment cores for age-class distributions	1674–1969	low-severity fires		
IDF	ww (?)	stand-maintaining 4–50, stand-replacing 250	Agee et al. (1990)	Desolation Peak, Skagit Valley, Washington State	dendrochronological analysis of fire scars and increment cores for 97 plots in 7 vegetation types	1573–1985	low-severity fires		
IDF	xh	stand-maintaining 4–50, stand-replacing 250	Riccius (1998)	Lower Stein Valley (xh2)	dendrochronological analysis of 356 fire scars (crossdated)	168[illegible]–19[illegible]2	low-severity fires		
IDF	xh	stand-maintaining 4–50, stand-replacing 250	Gray et al. (2002)	Glossy Mountain, near Ashcroft (xh2)	dendrochronological analysis of 13 fire-scarred trees (crossdated) and increment cores in elevational transect	1621–2001	low-severity fires		
IDF	xh	stand-maintaining 4–50, stand-replacing 250	Gray et al. (2002)	Spences Bridge (xh2)	dendrochronological analysis of 9–11 fire-scarred trees (crossdated) and increment cores in 2 elevational transects; includes IDFdk1 and PPxh2	1786–2001	low-severity fires		
IDF	xm	stand-maintaining 4–50, stand-replacing 250	Blackwell et al. (2002)	Churn Creek Protected Area	dendrochronological dating of fire scars (n = one 10-ha site, 8 trees)	1680–2000	low-severity fires		
IDF	xw	stand-maintaining 4–50, stand-replacing 250	none known						
MH	mm	350	Hallet (2001); Lertzman et al. (2002)	Fraser Valley 3 sites mm2/mmp	dating charcoal in lake sediment and soil	11 000 yr	fire		
MH	mm	350	Lertzman and Krebs (1991)	Cypress, Lower Mainland 1250 m of transects in 4 stands	area in canopy gap for turnover rates		gap processes		
MH	un		none known						

Range fire cycle / Mean return interval (yr)	Mean fire cycle / Mean return interval (yr)	Range in time-since-fire	Mean time-since-fire	Patch size	Remnant size	Comments	Zone	Subzone
1–94	6–7					• south aspect • forest cover maps mark IDFww area as CWHds, 1 transect includes ESSFmw	IDF	ww
6–23			1906–1969			did not use a period of reliability	IDF	ww
	52					• near meadow encroachment study of Lepofsky et al. (2000) • juxtaposition of forest types commonly not found together is believed to contribute to the relatively long MFI for the IDF plots • did not use a period of reliability	IDF	ww (?)
9–28 for 6 sampled river terraces	17		1972 (low severity)	most fires burned only a few ha		very small study area (28 ha)	IDF	xh
1–54	11					• south aspect • consider a point frequency, assume fires burn entire 40-ha transect	IDF	xh
north aspect: 1–54 south aspect: 1–54	north aspect: 12 south aspect: 10					consider a point frequency, assume fires burn entire 40-ha transect	IDF	xh
3–36	14						IDF	xm
							IDF	xw
	Median: 1200	50–9220 yr BP	Median: 1330			• note that comparing MFI from paleo data between different sites is appropriate when from point sources (small catchments or different points for soil record) or study area is known • fire interval calculated from dated charcoal samples which were > 300 yr apart	MH	mm
556–1111**				0.0025–0.13 ha		** depending on time to fill gaps, see text • Lertzman et al. (1996) also looked at gaps in MHmm1, but had only 3 plots	MH	mm
							MH	un

TABLE 1 *Continued*

Zone	Subzone	Guidebook mean return interval (yr)	Author	Location	Method	Period of record	Disturbance agent	Range in disturbance rates	Mean disturbance rate
MH	wh	350	none known						
MS	f	150	Reed (1994)	Kootenay TSA	maximum likelihood		stand-replacing events		
MS	dm1	150	Pollack et al. (1997)	Nelson Forest Region (dm1)	fitted age classes; negative exponential		stand-replacing events		
MS	dm1	150	Gray et al. (2002)	Columbia Lake, Invermere Forest District	dendrochronological analysis of 16 fire-scarred trees (crossdated) and increment cores in elevational transect including IDFdm2	1763–2002	low- to mixed-severity fires		
MS	dk	150	Pollack et al. (1997)		fitted age classes; negative exponential		stand-replacing events		
MS	dk	150	Masters (1990)	Kootenay National Park	time-since-fire distribution based on stand-origin map	1508–1928	stand-replacing fire		
MS	dk	150	Gray et al. (2002)	Lone Peak, Cranbrook Forest District	dendrochronological analysis of 17 fire-scarred trees (crossdated) and increment cores in elevational transect including IDFdm2	1736–2002	low- to mixed-severity fires		
MS	dc	150	none known						
MS	dv	150	none known						
MS	un		none known						
MS	xk	150	Gray et al. (2002)	Glossy Mountain, near Ashcroft	dendrochronological analysis of 16 fire-scarred trees (crossdated) and increment cores in elevational transect including IDFxh2, dk)	1735–2002	low- to mixed-severity fires		
MS	xv	150	none known						
PP	dh	stand-maintaining 4–50, stand-replacing 250	Stuart-Smith and Hendry (1998)	Invermere Forest District	1:20 000 air photo interpretation of remnants in 2 fires		mixed-severity fires		
PP	xh	stand-maintaining 4–50, stand-replacing 250	Riccius (1998)	6 terraces in Lower Stein Valley (xh2)	dendrochronological analysis of 336 fire scars (crossdated)	1683–1972	low-severity fires		
PP	xh	stand-maintaining 4–50, stand-replacing 250	Gray et al. (2002)	Murray Creek, near Spences Bridge (xh2)	dendrochronological analysis of 11 fire-scarred trees (85 scars crossdated) and increment cores	1596–2002	low-severity fires		

Range fire cycle / Mean return interval (yr)	Mean fire cycle / Mean return interval (yr)	Range in time-since-fire	Mean time-since-fire	Patch size	Remnant size	Comments	Zone	Subzone
							MH	wh
	51 (95% CI: 35–101)					does not incorporate age-dependent susceptibility, which is very likely significant in the MS	MS	?
	107					does not incorporate age-dependent susceptibility, which is very likely significant in the MS	MS	dm1
2–44	18					• south aspect only; stand-replacing event evidence on north aspect • consider a point frequency, assume fires burn entire 40-ha transect	MS	dm1
	108					does not incorporate age-dependent susceptibility, which is very likely significant in the MS	MS	dk
	60 (1508–1788) 130 (1788–1928)					study area combines MSdk and ESSFdk	MS	dk
1–43	14					• south aspect only; stand-replacing event evidence on north aspect in ESSFdk • consider a point frequency, assume fires burn entire 40-ha transect	MS	dk
							MS	dc
							MS	dv
							MS	mw
21–71	39					• south aspect only • consider a point frequency, assume fires burn entire 40-ha transect	MS	xk
							MS	xv
					single trees: 20–33 trees/ha average ± 1 SD clumps: 1.8 ± 1.3 ha islands: 6.8 ± 3.8 ha	fires subjectively selected and sample size very small (*n* = 2)	PP	dh
9–28	17		1972 (low severity)	most fires burned 2–4 ha		• very small study area (28 ha), topographically dissected	PP	xh
1–26	7					consider a point frequency, assume fires burn entire 40-ha transect	PP	xh

TABLE 1 *Continued*

Zone	Subzone	Guidebook mean return interval (yr)	Author	Location	Method	Period of record	Disturbance agent	Range in disturbance rates	Mean disturbance rate
SBPS	dc	100	Francis et al. (2002)	Chilcotin Plateau (60 000 ha of 307 000 ha study area)	field and dendrochronological verification of fire margins, stand-origin dates and air photo interpretation to extrapolate	1665–2001 (POR: 1831–2001)	low-, mixed- and high-severity fires		
SBPS	mc	100	Steventon (1997); Steventon (2001)	Lakes/Morice/Bulkley TSAs (Prince Rupert Region)	neg. exponential, truncated, rollback for logging, overlapping disturbances (Method 1: A, B; Reed et al. 1998)	1800–1970	stand-replacing events	0.06–0.09%/yr (90% CI)	
SBPS	mk	100	Francis et al. (2002)	Cariboo Region (98 200 of 327 300 ha)	field and dendrochronological verification of fire margins, stand-origin dates and 1:20 000 air photo interpretation to extrapolate	1700s–1961	low-, mixed- and high-severity fires		1869–1961: 1.67%/yr (includes SBSdw1 and dw2)
SBPS	xc	100	Douglas (2001)	Chilcotin Plateau	n = 13 trees (6 stands, not crossdated)	1834–1989	low-severity fires		
SBPS	xc	100	Francis et al. (2002)	Chilcotin Plateau (219 000 of 307 000 ha)	field and dendrochronological verification of fire margins, stand-origin dates and air photo interpretation to extrapolate	1665–2001 (POR: 1831–2001)	low-, mixed- and high-severity fires		
SBS	[illegible]	125	Zhang et al. (1999)	near McGregor Model Forest (10 sites within 165 000 ha)	dendrochronological dating of ring patterns in host and non-host species	1750–1990s	spruce bark beetle		
SBS	dh	125	none known						
SBS	dk	125	Steventon (1997); Steventon (2001)	Lakes/Morice/Bulkley TSAs (Prince Rupert Region)	forest inventory, neg. exponential, truncated, rollback for logging (Method 1: A, B)	1800–1970	stand-replacing events	0.06–0.13%/yr (90% CI)	

Range fire cycle / Mean return interval (yr)	Mean fire cycle / Mean return interval (yr)	Range in time-since-fire	Mean time-since-fire	Patch size	Remnant size	Comments	Zone	Subzone
	47 (1869–1961) 68 (1869–2001) (includes SBPSdc) 61 (1869–1961) SBPSdc only 64 ± 40 yr (from fire scars)			1922–1961: 1369 ± 5867 ha (mean ± SD) 32.5 (median) 35 042 ha (range from median) 38% < 50 ha	1922–1961: 34.4 ± 118.6 ha (mean ± SD) 7.1 (median) 1375 ha (range from median)	• field sampling was low intensity at each site (e.g., only 1 fire-scarred disk and 2 cores collected per fire margin) but spatially extensive • 91% of area originated during or since 1869 fire • assumptions behind fire cycle method violated as 2 large fire events affected at least 50% study area • also quantifies fire severity across landscape • provide patch size distribution	SBPS	dc
	91			40% of landscape in patches > 500 ha		• used forest inventory classes 3–7 and does not account for reburning of older patches • used age data from audit plots to examine inaccuracies in forest inventory data	SBPS	mc
	1869–1961 adjusted for overlap: 80 (includes SBSdw1 and dw2) 1922–1961 (assume no overlap): 170			• 1700s–2001: 325 ± 1490 ha (mean ± SD) • not adjusted for overlap		• field sampling was low intensity at each site (e.g., only 1 fire-scarred disk and 2 cores collected per fire margin) but spatially extensive • used time-since-fire map and attempted to account for overlapping fires with 1/3 overlap rule • assumptions behind fire cycle method violated as two large fire events affected study area • provide patch size distribution	SBPS	mk
5–44	14						SBPS	xc
	47 (1869–1961) 68 (1869–2001) (includes SBPSdc) 43 (1869–1961) SBPSxc only 45 ± 26 yr (from fire scars)			1922–1961: 1557 ± 4610 ha (mean ± SD) 140.8 (median) 36 639 ha (range from median) 36% < 50 ha	1922–1961: 19.4 ± 53.1 ha (mean ± SD) 6.8 (median) 623 ha (range from median)	• field sampling was low intensity at each site (e.g., only 1 fire-scarred disk and 2 cores collected per fire margin) but spatially extensive • 91% of area originated during or since 1869 fire • compare time-since-fire mapping and reconstructed individual fires • assumptions behind fire cycle method violated as 2 large fire events affected at least 50% study area • also quantifies fire severity across landscape • provide patch size distribution • other studies: Vera (2001); Hawkes et al., unpubl. data	SBPS	xc
40–100					90% of spruce killed in 1980s	same pattern found over 165 000 ha suggesting widespread high-severity outbreaks in past	SBS	–
							SBS	dh
	95					used forest inventory classes 3–7 and does not account for reburning of older patches	SBS	dk

TABLE 1 *Continued*

Zone	Subzone	Guidebook mean return interval (yr)	Author	Location	Method	Period of record	Disturbance agent	Range in disturbance rates	Mean disturbance rate
SBS	dw	125	DeLong (1998)	637 662 ha near Prince George	forest inventory, proportion in age classes 3 and 4	1911–1950	stand-replacing events	0.36–0.75 %/yr	0.55%/yr
SBS	dw	125	Francis et al. (2002)	Cariboo Region (dw1 and dw2, 327 300 including SBPSmk)	field and dendrochronological verification of fire margins, stand-origin dates and 1: 20 000 air photo interpretation to extrapolate	1700s–1961	low-, mixed-, and high-severity fires		1869–1961: 1.67%/yr includes SBSdw1 and dw2
SBS	mc	125	Steventon (1997); Steventon (2001); Cliff Manning Forestry Services (2001)	Lakes, Morice, Bulkley TSAs, Prince Rupert Region	forest inventory, neg. exponential, truncated, rollback for logging (Method 1-A, B)	1800–1970	stand-replacing events	0.06–0.09%/10 yr (80% CI)	
SBS	mc	125	DeLong (1998)	280 416 ha near Prince George	forest inventory, proportion in age classes 3 and 4	1911–1950	stand-replacing events	0.67–1.25%/yr	0.96%/yr
SBS	mh	125	none known						
SBS	mk	125	Andison (1996); DeLong and Tanner (1996)	entire subzone 790 000 ha north of Prince George	forest inventory, neg. exponential, truncated, rollback for logging, field work to divide 8 and 9 age class (Method 1-C)	1700–1954	stand-replacing events	0.07–0.4%/20 yr (rollback based on 80 yr MFI), 0.07–0.19% if no rollback years	
SBS	mk	125	DeLong (1998)	1 125 396 ha near Prince George	forest inventory, proportion in age classes 3 and 4	1911–1950	stand-replacing events	plateau: 0.42–1.16%/yr montane: 0.28–0.54%/yr	plateau: 0.79%/yr montane: 0.41%/yr
SBS	mm	125	none known						
SBS	mw	125	none known						
SBS	un	125	none known						
SBS	vk	200	Hawkes et al. (1997)	121 000 ha near McGregor Model Forest	forest inventory, proportion in age classes 3–7	1850–1950	stand-replacing events	0.016–0.085%/yr	mean 0.047

Range fire cycle / Mean return interval (yr)	Mean fire cycle / Mean return interval (yr)	Range in time-since-fire	Mean time-since-fire	Patch size	Remnant size	Comments	Zone	Subzone
133–181				56.7% of landscape in patches >1000 ha; mean, 76 ha; max, 7693; SD, 418		used age classes 3 and 4 to avoid effects of fire suppression, harvesting, reburns	SBS	dw
	1869–1961 adjusted for overlap: 60 includes SBSdw1 and dw2 1922–1961 (assume no overlap):170			• 1700s–2001: SBSdw1: 297 ± 1183 ha (mean ± SD); SBSdw2: 387 ± 1666 ha (mean ± SD) • not adjusted for overlap		• field sampling was low intensity at each site (e.g., only 1 fire-scarred disk and 2 cores collected per fire margin) but spatially extensive • used time-since-fire map and attempted to account for overlapping fires with 1/3 overlap rule • assumptions behind fire cycle method violated as 2 large fire events affected study area • provide patch size distribution	SBS	dw
	133					used forest inventory classes 3–7 and does not account for reburning of older patches	SBS	mc
	104			72% of landscape in patches > 1000 ha; mean, 296 ha; max, 19 030; SD, 1602		used age classes 3 and 4 to avoid effects of fire suppression, harvesting, reburns	SBS	ms
							SBS	mh
80–100				31% of landscape is in 10 000 ha+ patches	1–73 ha (3–15% of burns)		SBS	mk
	Plateau: 127 Montane: 244			plateau: 78% of landscape in patches > 1000 ha; mean, 179; max, 41 787; SD, 1858 montane: 74% in patches > 1000 ha; mean, 213 ha; max, 10 458; SD, 906		used age classes 3 and 4 to avoid effects of fire suppression, harvesting, reburns	SBS	mk
							SBS	mm
							SBS	mw
							SBS	un
1205–6250				23% of landscape in patches > 1000 ha; 0.08–13 549 ha (mean = 39)		• includes ESSFwk2/wc3 • age class 8 was avoided because of inaccurate ages. However, because 90% of landscape fell in age class 8, it follows that return intervals are relatively long.	SBS	vk

TABLE 1 *Concluded*

Zone	Subzone	Guidebook mean return interval (yr)	Author	Location	Method	Period of record	Disturbance agent	Range in disturbance rates	Mean disturbance rate
SBS	vk	200	DeLong (1998)	395 603 ha near Prince George	forest inventory, proportion in age classes 3 and 4	1911–1950	stand-replacing events	0.02–0.1%/yr	0.06%/yr
SBS	wk	200	DeLong (1998)	583 700 ha near Prince George	forest inventory, proportion in age classes 3 and 4	1911–1950	stand-replacing events	plateau: 0.29–0.44%/yr montane: 0.15–0.24%/yr	plateau: 0.37%/yr montane: 0.2%/yr
SWB	dk	200	none known						
SWB	dks	200	none known						
SWB	mk	200	Rogeau (2001)	Mackenzie TSA 1 327 000 ha 1 549 306 ha (4 different terrain units)	• spatially explicit modelling of historic fires in different terrain units (see comment) • also air photo interpretation of 1950s set and analyses of MOF fire database	c. 1860	stand-replacing events	0.3–0.5%/yr	0.32–0.45%/yr
SWB	mks	200	none known						
SWB	un	200	none known						
SWB	vk	200	none known						
SWB	vks	200	none known						

Note: All footnotes referenced in this table are found in the Comments column.

Range fire cycle / Mean return interval (yr)	Mean fire cycle / Mean return interval (yr)	Range in time-since-fire	Mean time-since-fire	Patch size	Remnant size	Comments	Zone	Subzone
	1666			13% of landscape in patches >1000 ha: mean, 62 ha; max, 1082; SD, 146		used age classes 3 and 4 to avoid effects of fire suppression, harvesting, reburns	SBS	vk
	plateau: 270 montane: 500			plateau: 38% in patches >1000 ha: mean, 96; max, 2514; SD, 270 montane: 39% in patches >1000 ha: mean, 74 ha; max, 1931; SD, 224		used age classes 3 and 4 to avoid effects of fire suppression, harvesting, reburns	SBS	wk
							SWB	dk
							SWB	dks
60–330	220–303 (± 18, 1 SD)			MOF fire database 1942–1991: 2272 ± 3526 ha (average ± 1 SD) 963 ± 2332 depending on region		• since details on verification and calibration of the model used (STANDOR) and are not provided, results should be interpreted with care • 4 units had some proportion of BWBS, SWB, and SBS • historic regimes simulated using probability of ignitions based on lightning ignitions in MOF database >1950	SWB	mk
							SWB	mks
							SWB	un
							SWB	vk
							SWB	vks

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2 A CATALOGUE OF QUANTITATIVE METHODS FOR ESTIMATING HISTORICAL VARIABILITY AND OTHER ATTRIBUTES OF NATURAL DISTURBANCES

Brigitte Dorner, Holger Sandmann, and Carmen Wong

2.1 Introduction

Natural disturbances are an essential component of the dynamics of forested landscapes. They have historically maintained structural elements and diverse forest conditions that provide critical habitat elements for many species (e.g., Bunnell 1995). Natural disturbances also have economic impacts. Despite often intensive efforts by forest managers to suppress or contain their occurrence, natural disturbances continue to affect the availability and commercial value of timber across large parts of the landscape. Several types of natural disturbances, notably wildfire, insect epidemics, and storm events, have long-term and often spatially extensive effects on the distribution of seral stages and the availability of harvestable wood.

In recent years, several studies have used computer models to quantify the expected economic and ecological consequences of such disturbances. For example, Martell (1994) estimated that an annual burn rate of 1.5% in the managed forests of Ontario would reduce the sustainable level of harvest by 35%. Similarly, a study by Olivotto Timber (1999) concluded that current rates of natural disturbances in the Cassiar Iskut-Stikine LRMP (in northwestern British Columbia) reduce sustainable rates of harvesting by at least 25%. A stand-level simulation of root rot dynamics in the West Arm Demonstration Forest (in southeastern British Columbia) estimated impacts on different scenarios of harvesting practices to range from 7 to 25% (Greenough et al. 1999). Klenner et al. (2000) examined distributions of seral stages. They calculated that in a dry montane landscape of southern British Columbia subject to both harvesting and wildfire, the total area in old-growth reserves would have to encompass at least 21.5% of the landscape to maintain old seral stages at the desired level of 15%.

Despite the common message, that relatively small annual rates of disturbance translate into significant long-term effects, current methods for projecting timber supply and non-timber values in British Columbia's forest regions do not consider natural disturbances as a major factor. Moreover, limited knowledge about the complex spatio-temporal dynamics of natural disturbances has led timber supply analysts to reduce highly variable processes to static events. For example, the most recent Timber Supply Review for the Arrow Timber Supply Area incorporates stand-replacing disturbance events as a static annual reduction, termed "unsalvaged losses," of approximately 5.7% (28 720 m^3, i.e., ~20 ha/yr), deducted from the current level of allowable annual cut (AAC) (550 000 m^3) (Pedersen 2001). In addition, stand-maintaining disturbances, such as root rot, blister rust, and small windthrow gaps, are partially included in the analyses by a further reduction of 5–15% of the estimated harvestable volume, referred to as operational adjustment factors (OAFs) (B.C. Ministry of Forests 2000).[23] In principle, the inclusion of unsalvaged losses and OAFs are credible tools to account for the cumulative impact of natural disturbances during the planning horizon of a timber supply analysis. However, the current quantification of disturbance-induced losses are little more than best guesses (e.g., see Pedersen 2001, pp. 53–54).[24] Limited data are available about the spatial and temporal variability of natural disturbances, interactions among disturbance agents, changes to forest succession or species composition initiated by specific disturbances, interactions between anthropogenic and natural disturbances, and long-term trends in ecosystem dynamics.

Irrespective of whether the goal is to improve the predictive capacity of timber supply analysis or to formulate management guidelines for maintaining biodiversity, the first step toward incorporating natural disturbances is to compile and evaluate currently available analytical tools for obtaining a description of natural disturbance dynamics. Quantitative information on spatial and temporal attributes of natural disturbances can be obtained only by examining direct and indirect evidence left on the landscape by past disturbance events. In this part of our report, we catalogue quantitative methods for estimating the historical frequency and variability of natural disturbances.

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[23] Note that these adjustments are meant to reflect only the wood volume that cannot be utilized, not the total wood volume affected by disturbances.

[24] See also the section on operational adjustment factors in the B.C. Ministry of Forests 1997 Growth and Yield Discussion Paper, available at http://www.for.gov.bc.ca/resinv/g%26y/projects/monitor/Discuss/Contents.htm.

The choice of a method for reconstructing historical disturbance frequency depends on several factors, including the type of disturbance that predominates in a landscape (e.g., stand-maintaining vs. stand-replacing disturbances), the characteristics of the expected disturbance regime, and the types of data available to the analyst. The methods described in this catalogue focus mainly on reconstructing the (point) *frequency* of disturbance events, or mean interval between consecutive disturbances at a location (see the glossary for a more detailed description of different measures of disturbance frequency). However, we emphasize that knowledge about other attributes, including size, severity, and duration, is required for a complete understanding of disturbance as a dynamic landscape-shaping process.

In the following sections, we provide a step-by-step guideline of how to identify one or more appropriate method to select, prepare, use, and analyze available data. In addition, the glossary—found at the end of this document—concisely describes all technical and mathematical terms used in this document. Note that this document can give only a broad overview of methods commonly used to analyze disturbance history. Readers wishing to study disturbance history should consult the references listed to acquaint themselves with available methods and their respective limitations. In addition, an interactive Microsoft EXCEL tutorial on methods for analysis of fire frequency (see Fall 1998) is available from the Forest Ecology Laboratory at the School of Resource and Environmental Management, Simon Fraser University.[25]

2.2 Suggested Sequence of Data Collection and Analysis

The following seven steps provide a logical sequence for our suggested approach towards reconstructing a quantitative description of historical disturbance dynamics. The first four steps—background research, data collection, selection of method, and data analysis—are required to complete a meaningful quantitative analysis. The remaining three steps, listed in order of increasing complexity, are optional but highly recommended approaches for learning about the *spatial* characteristics of past disturbances and, in the case of dynamic modelling (Step 7), for exploring the *interactions* of spatial and temporal attributes.

Step 1: Get to know the natural disturbances in your area

Required Obtain the best available qualitative and quantitative description of disturbance dynamics in the study area, using published studies, existing databases, and expert opinion. In particular, the following issues should be addressed as best as possible; the answers to these questions determine which types of data and quantitative methods may be used to reconstruct disturbance frequency and other aspects of natural landscape dynamics:

a. What are the primary disturbance agents in the area?
b. Are there substantial differences in disturbance dynamics throughout the area? If so, the study area should be subdivided into sections with similar disturbance dynamics.
c. What are the characteristics of each of the disturbance agents active in the area? Characteristics include frequency, intensity, size, and severity (degree of mortality). Are all stands equally susceptible? If not, what are the characteristics that affect the susceptibility of a stand: age, species composition, size, stand structure, position in the landscape, previous disturbance history (such as windfall and mistletoe)?
d. What is the estimated disturbance return interval for individual disturbance agents? For what period of time in the past? What is the estimated disturbance return interval for all disturbance agents combined? What is the estimated disturbance return interval for predominantly stand-maintaining agents versus stand-replacing agents?
e. What is the expected variability in disturbance dynamics? Are disturbances endemic, or do they occur as distinct events? Do disturbances occur as large and contiguous events in space and/or time, or do they tend to occur as small, widely scattered events in space and/or time?
f. How might different disturbance agents interact? Does the occurrence of one agent increase the

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[25] The latest version can be downloaded from http://www.rem.sfu.ca/forestry/.

likelihood of another (e.g., mountain pine beetle outbreaks may increase fuel loading and the likelihood of fire)?

Our literature review of disturbance regimes found in British Columbia (see Part 1, this report) can provide a starting point to address these questions. Another recently completed project, *Towards a Taxonomy of Natural Disturbances in British Columbia*, summarizes current knowledge about a wide range of attributes for 39 disturbance agents found throughout the province (Wong 2001). However, further reviews should be conducted to take advantage of any available local knowledge and recent studies that were not available when this report was compiled.

Step 2: Collect all available disturbance-related data

Required Determine the types of data potentially available to reconstruct disturbance history in the study area. If high-severity disturbances, such as crown fires, were common, the primary evidence of disturbance dynamics available will likely be the mosaic of stand ages created across the landscape. Forest Inventory Planning (FIP) data (B.C. Ministry of Forests 1998) may be used to represent this stand age mosaic. If high-severity disturbances were rare and low- or medium-severity disturbances predominate, data on occurrence of these types of disturbances may need to be collected in the field (see catalogue section below). Where fire is a dominant disturbance agent, the provincial fire atlas (Parminter 2000) can be used in several ways to obtain quantitative information about the fire regime in the area (however, see discussion in Part 3, Section 3.2).

Step 3: Choose an appropriate quantitative method from the catalogue

Required Methods for quantitative analyses of disturbance dynamics are selected based on the expected characteristics of the historical disturbance regime (e.g., stationary vs. non-stationary dynamics, age-dependent vs. age-independent susceptibility to disturbance) and the type of evidence left in the landscape (e.g., time-since-disturbance vs. disturbance interval data). The key in Section 2.3 will help in choosing the method or methods appropriate for the expected historical disturbance dynamics and the types of data available. In many cases, expert opinion and studies done in similar areas may be the only sources of information until suitable field data can be collected.

Step 4: Prepare, analyze, and interpret the data

Required If independent alternative methods of analysis are available, we recommend using as many of them as possible to get a better understanding of the degree of uncertainty inherent in estimates of historical disturbance rates for the area. If estimates differ substantially, try to identify the reasons for the observed differences. Some of the estimates may have to be discarded as unreliable due to flaws in the data, or because the results suggest that historical disturbance dynamics do not meet the assumptions made in the method.

In other cases, differing estimates may indicate incomplete understanding of the disturbance dynamics in the area (e.g., which are the primary natural disturbance agents, what is the spatial variation in disturbance regime).

Step 5: Determine the spatial characteristics of disturbance patches

Optional A characterization of size and shape distributions requires spatially explicit records of past disturbance events. Some of these data can be extracted from forest cover maps and their associated database, field studies, and the provincial fire atlas. However, most spatially explicit records of disturbances cover only the most recent period and are likely influenced by disturbance suppression and other forest management activities.

Step 6: Examine landscape-level patterns and distributions

Optional Landscape characteristics, such as spatial pattern and distribution of stand ages, stand structure, and species composition, can be analyzed by simple summary statistics as well as complex GIS algorithms. Some of the methods contained in the catalogue directly allow limited reconstruction of historical landscape structure. If harvesting or other management activities have substantially altered the landscape in question, additional information on natural or semi-natural pattern can be obtained by studying nearby unharvested areas (e.g., Dorner 2002) and/or by using simulation modelling (see Step 7).

Step 7: Explore spatio-temporal dynamics with a landscape model

Optional Spatially explicit models of forest dynamics, such as FPS/Atlas (Nelson 1999), LANDIS (Sachs 1999), LANDSUM (Keane et al. 1997), Prognosis EI (Greenough et al. 1999), SELES (Fall and Fall 1996, 2001), and TELSA (Klenner et al. 1997) offer valuable and interactive tools to compile and experiment with existing knowledge. In particular, such models help to (1) test hypotheses about spatio-temporal dynamics of natural disturbances; (2) explore long-term interactions between natural disturbances and forest management; and (3) visualize aspects of landscape dynamics that cannot be reconstructed directly from empirical data.

2.3 Key to the Methods Catalogue

This key is meant to help in selecting the appropriate method(s) for analyzing data about natural disturbances. Methods are organized into groups based on the type of data source required for each method. A sequence of three decisions will lead to finding the appropriate method(s): (1) the type of the disturbance regime encountered in the study landscape; (2) the type(s) of data available; and (3) the expected characteristics of the disturbance regime. In the key, "groups" combine similar sets of input data, whereas "methods" denote the different analytical procedures. Note that each criterion has opportunities for selecting more than one link (e.g., a spatially separate mix of disturbance regimes, multiple sets of available data, or different expected characteristics). As mentioned in Section 2.2, Step 4, using most or all independent alternative methods is highly recommended.

Criterion 1: Data available for analysis

Disturbance regime is predominantly **stand-replacing** (i.e., high severity/catastrophic)

1a.	Stand origin or year of disturbance	**Group 1**
1b.	Year, size, and location of disturbance	**Group 2**
1c.	Record of intervals between consecutive disturbances	**Group 3**
1d.	Few or incomplete data; expert opinion or literature review only	**Group 6**

Disturbance regime is predominantly **stand-maintaining** (i.e., low severity)

2a.	Stand origin or year of disturbance	**Group 1**
2b.	Year, size, and location of disturbance	**Group 2**
2c.	Record of intervals between consecutive disturbances	**Group 3**
2d.	Stand structure attributes	**Group 4**
2e.	Spatial and/or temporal attributes of canopy gaps	**Group 5**
2f.	Few or incomplete data; expert opinion or literature review only	**Group 6**

Disturbance regime is **mixed** (i.e., a combination of stand-replacing and stand-maintaining events)

3a.	Stand origin or year of disturbance	**Group 1**
3b.	Year, size, and location of disturbance	**Group 2**
3c.	Record of intervals between consecutive disturbances	**Group 3**
3d.	Stand structure attributes	**Group 4**
3e.	Spatial and/or temporal attributes of canopy gaps	**Group 5**
3f.	Few or incomplete data; expert opinion or literature review only	**Group 6**

Criterion 2: Expected characteristics of disturbance regime

Group 1: Methods based on time-since-disturbance data

G1a.	Temporally and spatially homogeneous disturbance regime. The entire area has experienced the same disturbance regime and there was no change in disturbance regime over period of data record (i.e., stationary in time and homogeneity in space); disturbance patches are small relative to landscape and disturbance events are distributed evenly throughout time and space	**Method 1-A**
G1b.	Temporally heterogeneous and spatially homogeneous disturbance regime. All age classes are equally susceptible to disturbance; distinct historical epochs can be defined within which the disturbance regime can be assumed to be constant (i.e., stationary in time)	**Method 1-B**
G1c.	No assumptions about temporal dynamics. Spatially homogeneous disturbance regime, with no assumptions about temporal dynamics; susceptibility to disturbance may be age-dependent, though relative susceptibility for different age classes is a required input to the method	**Method 1-C**

Group 2: Methods based on disturbance year *plus* spatial location and extent data

G2a.	Complete record of point samples or maps, temporally homogeneous (if extrapolated beyond range of observations)	**Method 2-A**
G2b.	Complete spatial record of disturbance events, homogeneous spread of disturbances	**Method 2-B**

Group 3: Methods based on record of intervals between consecutive disturbances

G3a.	Temporally stationary disturbance regime; spatial homogeneity	**Method 3-A**
G3b.	Frequent disturbances and/or long record of disturbance events at each site	**Method 3-B**
G3c.	Disturbances are sufficiently large in relation to the sampling scheme; the grid resolution of sample points captures all disturbance events significantly contributing to disturbed area	**Method 3-C**

Group 4: Methods based on stand structure and other proxy data

G4a.	Relevant stand structure attributes and/or other proxy data are available	**Method 4-A**

Group 5: Methods based on spatial and/or temporal attributes of canopy gaps

G5a.	Proportion of forest in canopy gaps	**Method 5-A**

Group 6: Methods based on no or very limited primary data

G6a.	No adequate disturbance or proxy data are available for area of interest; disturbance regime of reference area is similar to that of study area	**Method 6-A**

Final Choice of Methods

Method 1-A. Fitting a function to the frequency distribution of time-since-disturbance data .... **page 73**
Method 1-B. Maximum-likelihood estimate of disturbance frequency .... **page 74**
Method 1-C. Rollback in time of the time-since-disturbance distribution .... **page 75**
Method 2-A. Disturbance frequency from a list of disturbance records (Natural Fire Rotation method) **page 76**
Method 2-B. Disturbance frequency from area interval and size data .... **page 77**
Method 3-A. Mean disturbance interval from pooled interval data .... **page 79**
Method 3-B. Disturbance frequency from the interval distribution on a site .... **page 80**
Method 3-C. Reconstruct maps of disturbance extent for individual disturbance years .... **page 80**
Method 4-A. Process-based modelling to derive disturbance regimes .... **page 80**
Method 5-A. Turnover time of forests with canopy gaps .... **page 81**
Method 6-A. Synthesis of relevant publications .... **page 81**

2.4 Catalogue of Quantitative Methods

The following methods are available for quantitative analysis of disturbance history data. The methods are divided into six groups based on the type of disturbance data that are available. Each method is described by its use, ideal sampling method for data, and analyses to determine disturbance frequency. Unless explicitly stated otherwise, the common output of all the methods described below is point disturbance frequency, or the *mean interval between disturbances for each point (or small forest stand) in the landscape.*

Group 1: Methods based on time-since-disturbance data

Data description: A map or representative point sample, giving *time elapsed since the most recent disturbance event* (in years). When forest dynamics are dominated by relatively frequent[26] occurrence of disturbances that kill large patches of trees, the resulting pattern across the landscape is a mosaic of predominantly even-aged stands. Because the canopy in these stands consists mainly of a cohort of trees that regenerated shortly after the last major disturbance event, the age of the trees in the stand can serve as a proxy for the time the stand has gone without experiencing a major disturbance (e.g., Agee 1993; Johnson and Gutsell 1994). Thus, time-since-disturbance datasets typically consist of maps or samples of stand age.

Potential scope: Any disturbance type for which time-since-disturbance data can be obtained.

Typical use: Estimate disturbance frequency in a landscape dominated by high-severity disturbances that occur in contiguous patches, notably crown fires.

Corresponding Vegetation Resources Inventory (VRI) or FIP fields, or fields that may serve as proxy: Year of stand origin or current stand age.

Other data available in provincial archives: Audit plot data and similar age data from sample plots can be used as auxiliary data to verify VRI or FIP age information.

Ideal data collection procedure:

a. Grid of sample points: To obtain a representative point sample, use a regular grid of sample points or a random sampling strategy. Time since disturbance at a sample point can often be established using dendrochronological methods (e.g., analysis of tree rings to estimate stand origin dates).
Additional recommended procedure: Oversampling, to determine dependence of results on scale of sampling grid. For part of the study area, the number of sampling points should be increased by a factor of four, corresponding to a doubling of grid resolution. Analyses can then be run in parallel on both the regular and the oversampled datasets to establish the influence of sampling resolution on results.
Alternatively, use computer simulation to determine implications of sampling decisions on

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[26] In relation to the typical lifespan of canopy trees within the area.

accuracy of results (Fall 1998). To accomplish this, first run a spatially explicit simulation of best-guess historical disturbance dynamics in the area. The simulation should record both actual long-term disturbance frequency and time-since-disturbance at each point in the landscape. If applicable, the synthetic time-since-disturbance record should then be "degraded" to account for natural processes that would normally affect the accuracy of sampled time-since-disturbance dates. For example, for a crown fire system, such a "degradation" process might add a random error term to the synthetic data to represent regeneration delay and uncertainty in reconstructed stand age. Finally, the degraded synthetic data is sampled, using a range of sampling protocols. The datasets obtained through one or more proposed sampling protocols are then analyzed to determine disturbance frequency, and results are compared with the actual disturbance frequency used in the simulation experiment.

Although this approach to testing the reliability of disturbance history methodology is flexible, its usefulness depends on whether the simulation was able to capture the essential characteristics of the natural system. Thus, simulation scenarios must incorporate all relevant key characteristics, and simulation experiments may have to be repeated if field-based observations suggest that disturbance dynamics were not anticipated correctly (Fall 1998).

b. Remotely sensed data: Where possible, use remotely sensed data to delineate stands with the same origin date and/or the same date of last disturbance, then determine the date of disturbance using dendrochronological methods.

   Additional recommended procedure: Further field sampling of the date of stand origin, with multiple plots across stand boundaries and within stands, to determine the accuracy of boundaries outlined by remote sensing.

Analysis Methods:

Method 1-A: Disturbance frequency from the time-since-disturbance distribution (Fire cycle method)

Principle: Disturbance occurrence is modelled as a stationary statistical process, typically a Poisson process. The expected shape of the standing age distribution is derived from the statistical process model adopted. If disturbance occurrence is modelled as a stationary Poisson process and all forest types are assumed to be equally susceptible to disturbance, the expected shape for the time-since-disturbance distribution is a negative exponential. When susceptibility to disturbance is considered to be age-dependent, a reverse cumulative Weibull function is most commonly used to describe the expected shape of the time-since-disturbance distribution.

Disturbance frequency is then calculated from the best-fit derivative (slope) of the function describing the expected shape of the time-since-disturbance distribution to the observed data.

Assumptions:

a. Stationary (i.e., the disturbance regime does not change over time).
b. Spatially homogeneous disturbance regime (i.e., all stands face the same probability of disturbance, irrespective of their location in the landscape).
c. No spatial or temporal "patchiness" (autocorrelation) (i.e., disturbance affects one small area at a time). There are no very large disturbance patches and there is little variation in the area disturbed from year to year.

Strengths: Simple, easy to apply. Although few, if any, real forests meet the full list of assumptions, simulation experiments (Lertzman et al. 1998) indicate that the method works well, provided the disturbance regime is indeed stationary and disturbances are relatively small (in relation to study area size) and evenly distributed throughout time and space.

Limitations:

a. In many areas, various levels of anthropogenic influences over the last century have likely affected disturbance regimes. Thus, stationarity should probably not be considered the default assumption for more recent natural disturbance dynamics. In addition, factors such as mid- and long-term climatic fluctuations may create non-stationarity in disturbance dynamics (Clark 1988). Many disturbance history studies have reported evidence of episodic disturbance regimes where large, infrequent events form a large proportion of overall disturbance activity (e.g., Turner et al. 1993). Age distributions for many forest landscapes do not exhibit the continuous downward slope in area for older forest, which is characteristic for steady-state age distributions resulting from a stationary disturbance regime. If a non-stationary regime or highly episodic disturbance regime is suspected, Methods 1-B or 1-C may be more appropriate.
b. To work properly, the method requires a full, un-

censored record of stand age distribution. In particular, the fitting algorithm is very sensitive to the amount of area in very old age classes. In reality, it is difficult or impossible to accurately assess the size and age of these old forest patches because they tend to be very small and stand age may exceed the lifespan of the oldest tree in the stand. This is known as the "missing tail problem" (Finney 1995).

References: Van Wagner (1978); Johnson and Van Wagner (1985); Johnson and Gutsell (1994).

Notes: This method has been widely applied in the literature, but is now largely superseded by the statistically more rigorous maximum-likelihood estimators described in Method 1-B. In particular, those looking for a formal method for calculating confidence intervals for process rate or to break up their analysis period into separate epochs with distinct disturbance regimes should refer to Method 1-B or 1-C.

Method 1-B: Maximum-likelihood estimate of disturbance frequency

Principle: Maximum likelihood estimates (MLEs) provide a statistically rigorous way of deriving parameter estimates for process rate. The conceptual approach underlying this method is the same as in Method 1-A. Disturbance occurrence is modelled as a Poisson process, which is assumed to be stationary over distinct historical epochs, representing periods for which distinct disturbance regimes are hypothesized. For example, researchers might want to distinguish between a "pre-settlement," "early-settlement," and "modern forest management" period. Disturbance frequency is derived by comparing forested area disturbed during an epoch to total forested area that has survived from the end of that epoch into the present. Disturbance frequency for each epoch is calculated based on the negative exponential model or the Weibull model as the expected shape of the time-since-disturbance distribution (see Method 1-A).

Assumptions: The use of the negative exponential model implies that the disturbance regime for each epoch corresponds to the assumptions made in Method 1-A, although the disturbance regime is allowed to vary between epochs and the statistical model formally accounts for spatial autocorrelation in disturbance occurrence (i.e., patchiness). In general, the standing age distribution does not supply enough information to distinguish between age-dependent susceptibility to disturbance and changes in disturbance frequency over time (Reed et al. 1998). Thus, although an MLE estimator for the Weibull function is available, separation into distinct time periods is generally possible only under the assumption that all susceptibility to disturbance is independent of stand age. Consequently, researchers must choose between allowing for age-dependent susceptibility to disturbance and subdivision into different historical epochs.

Strength: Provides confidence intervals for calculated disturbance frequency, and a statistically clean way of temporal partitioning, and allows testing for statistical significance of differences between process rates estimated for different epochs.

Limitations: Temporal partitioning into distinct time periods is available only where susceptibility to disturbance is not age-dependent. The validity of statistical inferences relies on all model assumptions being met. Thus, applicability of statistical inferences in practice may be questionable. Similar to Method 1-A, this procedure can, with reasonable accuracy, assess historical disturbance rates even where assumptions are not fully met.

References: Reed (1994, 1997); Reed et al. (1998).

Notes: The confidence interval calculated in this method represents confidence in disturbance frequency as the essential parameter of an abstract statistical model of disturbance regime (see also Armstrong 1999). The question addressed with this confidence interval is: *Given a range of disturbance regimes with different parameters, which ones might have produced the disturbance history observed on the landscape?* Thus, the confidence interval does *not* address the question of how closely the calculated estimate of disturbance frequency approximates the disturbance frequency actually experienced by the landscape over the period of historical record. The key question to be addressed to obtain confidence intervals that express this second kind of uncertainty would be: *Given the deviations from model assumptions and data sampling errors, what is the expected bias and error in estimated disturbance frequency?* (see Fall et al. 1997; Fall 1998; Dorner 2002; Dorner and Lertzman, in review).

The wide confidence intervals often reported (e.g., in Reed et al. 1998; Armstrong 1999; Weir et al. 2000) indicate that, for systems characterized by high-severity disturbance events, attempts to reason about disturbance dynamics based on abstract statistical models of disturbance regime will likely be plagued by low statistical power. Thus, questions such as *Do* *two areas have a different disturbance regime?* or *Could the two observed disturbance histories have arisen from the same conceptual process?* will often be difficult to answer conclusively. On the other hand, wide confidence intervals by themselves do not necessarily imply that historical disturbance frequency, as an empirical quantity, cannot be accurately reconstructed from time-since-disturbance data.

Method 1-C: Rollback of the time-since-disturbance distribution

Principle: The standing age distribution is "rolled back" in time by successively reassigning disturbed forest to older age classes. This rollback process explicitly reconstructs the standing age distribution over the entire historical period of record. Once historical standing age distributions are reconstructed, disturbance frequency can be calculated by simply comparing area in the youngest age class (i.e., area recently disturbed) to total forested area. To determine how much of the area in the youngest age class should be assigned to each of the older age classes in each rollback step, the Rollback Method requires an *a priori* estimate of relative susceptibility to disturbance for different age classes. The function that describes relative susceptibility to disturbance may be specified to change over time, to reflect, for example, a switch from natural disturbance regimes to timber harvesting as the primary disturbance agent.

Assumptions: Spatially homogeneous disturbance regime (see Methods 1-A and 1-B).

Strengths: Does not rely on steady-state age distribution nor assumes a stationary disturbance regime. The reconstructed time series of historical standing age distributions provides information beyond disturbance rotation. Thus, quantities such as temporal variability in disturbance rates and historical range of variability in seral stage distribution, which are directly relevant for forest management, can be estimated without recourse to a steady-state model of forest dynamics.

Limitations:

a. Unlike Method 1-B, this approach can be used to analyze temporal variation in systems with age-dependent susceptibility to disturbance. However, it does not reconstruct age-specific susceptibility of disturbance from the data. Since the standing age distribution does not give enough information to distinguish between age-dependent susceptibility to disturbance and changes in disturbance frequency over time (Reed et al. 1998; see also Method 1-B), *a priori* assumptions must be made either about the relative susceptibility to disturbance for different age groups or about the temporal pattern of disturbance rates.

b. Like Methods 1-A and 1-B, this approach is based on the premise that the amount of forest in the landscape aged *t* years bears a direct relationship to the amount of forest area disturbed *t* years ago. Consider a cohort of forest established *t* years ago. The area in this cohort represents the proportion of total forest area disturbed that year and thus is a direct measure of disturbance rate for that year. As the cohort ages, it loses a proportion of its area to subsequent disturbances. However, the area of the original cohort surviving to the present is still proportional to the area originally disturbed *t* years ago and can thus be used to reconstruct disturbance rates for that year, assuming one can discount the stochasticity in natural disturbance dynamics. This last assumption is justified only if the study area, as well as the area in the original cohort and the cohort area expected to survive to the present, are large relative to the typical size of disturbance patches, allowing statistical fluctuations to cancel out over time and space. In general, the older a cohort, the less of its area survives and the more susceptible this remnant area becomes to being either completely missed or completely removed by subsequent disturbances. Thus, the Rollback Method is most reliable when applied to large areas and more recent time periods.

c. Unlike Method 1-B, this approach does not provide statistical confidence intervals for disturbance frequency (see also notes on Method 1-B).[27]

References: DeLong and Tanner (1996); Andison (2000); Dorner (2001, 2002); Dorner and Lertzman (in review).

Notes: Simulation experiments indicate that even a fairly substantial violation of the spatial homogeneity assumption, such as a postulated two-fold increase in disturbance rate across the study area (e.g., due to temperature or precipitation gradients), has only a minor effect on the accuracy of results (Dorner 2002; Dorner and Lertzman, in review). However, where disturbance rates are known to be strongly dependent on site-specific factors, this method should not be applied without prior landscape stratification into susceptible and less susceptible areas.

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[27] In Part 3 of this report, we use the Rollback Method to reconstruct historical variability in disturbance rates for the Arrow Forest District, and provide further details about the method's strengths and limitations.

Group 2: Methods based on disturbance year plus spatial location and extent data

Data description: A database containing for each disturbance event:

a. disturbance year,
b. approximate spatial location of the disturbance event, and
c. spatial extent of the disturbance.

Potential scope: Any disturbance type.

Typical use: Estimate disturbance frequency from fire tower data, aerial surveys, or paleoecological records. Note: the methods described in this section do *not* assume that individual disturbance events were mapped. If a series of maps of individual disturbance events is available, readers should also consult the methods in Group 3, which use the additional information provided by a complete spatial record of past disturbance activity.

Corresponding VRI or FIP fields, or fields that may serve as proxy: FIP disturbance information (year and type of most recent disturbance).

Other data available in provincial archives:

a. Provincial fire database
(1950–1994, non-spatial digital version of provincial fire atlas, which contains approximate location of the fire as well as final fire size and perimeter).
b. Digital fire atlas (currently in preparation; J. Parminter, B.C. Ministry of Forests, Research Program, pers. comm., 2002).
The old atlas (1919 to early 1940s; smallest fires recorded: 10–15 ha) and the new atlas (early 1940s to 1988) record "wildfires" only; prescribed fires were not recorded. Only the final fire perimeter is reported; there is no information on unburned remnants within this perimeter. Scale of original paper maps is mostly 1:125 000. In case of discrepancies, digital forest cover boundaries should be considered more accurate than the boundaries recorded in the fire maps. For the period before 1960, the fire atlas data are incomplete and biased towards central and southern British Columbia. Maintenance of spatial maps has not been consistent since 1988 (Parminter 2000).
c. Canadian Forestry Service (CFS) fire database
(1980–1995, fires >200 ha only).
d. CFS pest data archives (FIDS).
Accuracy and scale similar to fire database; for detailed descriptions see
http://web.pfc.forestry.ca/health/pests/

Ideal data collection procedure: Establish a regular grid of field sample plots and determine historical disturbance occurrence for each plot using dendrochronological methods (see also recommended data collection procedures for Group 3). The resolution of the grid should reflect the expected fire size in the area (i.e., the smaller the fires, the finer the grid). Use this sample grid directly (see Note (b) for Method 2-A) and/or reconstruct maps of individual disturbance events by interpolating disturbance parameters between sample locations (see Method 3-C). Auxiliary information, such as air photos, VRI, or FIP data, or a set of rules derived from general knowledge about disturbance behaviour, may be used to aid in interpolation. If possible, different interpolation schemes should be used to quantify the effect of interpolation rules on analysis results (see Heyerdahl 1997).

Additional recommended procedure: Oversampling, to determine dependence of results on the scale of the sampling grid. For part of the study area, the number of sampling points should be increased by a factor of four, corresponding to a doubling of grid resolution. Analyses can then be run in parallel on both the regular and the oversampled datasets to establish the influence of sampling resolution on results.

Maintain a detailed spatial record of forest fires, pest outbreaks, and other disturbances, including a record of pre-disturbance vegetation cover and undisturbed remnants within the disturbance perimeter. In addition, a detailed spatial record of disturbance severity is desirable.

Additional recommendations: If different sources of disturbance records area available, cross-check these for completeness and accuracy of disturbance information.

Analysis Methods:

Method 2-A: Disturbance frequency from a list of disturbance records (Natural Fire Rotation method)

Principle: Disturbance frequency is calculated as:

$$\frac{\sum_{\textit{all disturbance events}} \textit{disturbance size}}{\textit{size of area} \times \textit{length of study period}}$$

Assumptions: The record of disturbance events is complete for the study period (i.e., no events went unrecorded).

Strengths: Simple and easy to apply.

Limitations:

a. The measure of disturbance frequency calculated using this method only reflects the disturbance return interval for each point in the landscape if the disturbance regime is spatially homogeneous. If disturbances occur at different rates in different parts of the landscape, the method still produces valid results in that it describes the average return interval. However, in this case the average return interval may be a poor descriptor of disturbance occurrence for some parts of the landscape. If different parts of the study area are suspected to have different disturbance regimes, the study area should therefore be stratified into more homogeneous sub-areas.

b. Unless complete spatial records of disturbance perimeters are available, determining the proportion of each disturbance that fell within the study area might be difficult. If individual disturbances are large relative to the size of the study area and the study area is not bound by physiographic features, such as mountain ranges or large water bodies, disturbances likely would have crossed the area's boundaries. If the distribution of disturbance sizes can be assumed to be homogeneous over larger spatial scales, this problem might be overcome by using a simple spatially explicit stochastic simulation model to simulate disturbance dynamics for the study area (see Method 2-B).

c. Complete records of disturbance occurrence and size are typically available only for the recent past. These records represent only a small sample of disturbance history and likely do not capture the full range of disturbance dynamics. In particular, rare, very large disturbance episodes may not have been recorded. This last issue may be addressed by fitting a parametric model to the disturbance size distribution and using the distribution, rather than the observed values, in the calculation (see Method 2-B). However, this approach relies on extrapolation of existing data. Although process-based models of fire size are available (Reed 2002), most models of disturbance size distribution proposed in the literature (Morrison and Swanson 1990; Armstrong 1999; Wimberly et al. 2000; Cumming 2001) are descriptive rather than process-based. Use of such empirical models to extrapolate from existing data is problematic because there is no inherent reason why the fitted function describes the disturbance regime beyond the range of observations.

d. Intensive forest management, such as disturbance suppression and alteration of stand structure and landscape pattern, may have influenced frequency, size, intensity, and spatial distribution of natural disturbances but this is hard to quantify. Thus, an analysis of natural disturbance regimes based only on recent data, such as the ones available from provincial archives, could be questionable.

References: Heinselman (1973); Hemstrom and Franklin (1982); Morrison and Swanson (1990); Cumming (1997); Heyerdahl (1997); Niklasson and Granstrom (2000); Jordan (2002); Rollins et al. (2001).

Notes:

a. In areas where more than one disturbance agent is significant, databases for different disturbance agents must be merged to obtain estimates of overall disturbance frequency.

b. This method is equally applicable to a set of point samples, with a list of disturbance dates given for each sample point. In this case, *disturbance size* becomes *number of sampling points recording the disturbance*, and *size of area* becomes *total number of sampling points*. This version of the method is often applied to disturbance interval datasets obtained through dendrochronological methods (e.g., Morrison and Swanson 1990; Heyerdahl 1997; Niklasson and Granstrom 2000); see also Group 3 on analyzing disturbance interval data, below.

Method 2-B: Disturbance frequency from area interval and size data

Principle: In addition to information on disturbance extent, this method requires information on the interval between consecutive disturbance events occurring anywhere in the study area. This latter information is easily obtained from the record of disturbance years. Rather than calculating disturbance frequency directly, this method uses the data indirectly to parameterize a stochastic model that simulates disturbance dynamics for the study area. The simulation proceeds by repeatedly drawing, at random, from a disturbance interval distribution a time interval for the next disturbance occurrence and then drawing a disturbance size from the disturbance size distribution. After running the simulation for a pre-defined time period, the total area disturbed is used with the formula from Method 2-A to calculate disturbance frequency. For this simplest case, all areas and forest types in the study area are assumed to be equally susceptible to disturbance, there is no spread of disturbance either into or out of the landscape, and the resulting disturbance frequency is simply given as the average interval between consecutive disturbances anywhere in the landscape times the average disturbance size. However, if the model of disturbance occurrence is made spatially explicit by initiating and spreading disturbances on a GIS map of the study area, more complex aspects of disturbance dynamics, such as site- or stand-specific probabilities of disturbance initiation and spread, can be incorporated. The records of simulated disturbance events produced by a spatially explicit simulation model can then be used as records of historical disturbances (i.e., disturbance frequency can be calculated either by using the formula from Method 2-A, or by using one of the methods from Group 3).

Assumptions: Dependent on the model implemented.

Strengths: Can be used where susceptibility of disturbance depends on stand or site characteristics. Provides site-specific estimates of disturbance frequency without requiring a detailed reconstruction of disturbance frequency by stand and/or site type. Can also be used to more completely describe historical landscape dynamics, including range of variability in seral stage proportions and pattern characteristics (e.g., Andison 2000; Wimberly et al. 2000).

Limitations: In general, the quality of the results will depend on the quality of the model and the accuracy of parameter estimates. Thus, the limitations outlined in Method 2-A regarding the limitations of datasets on disturbance size and occurrence apply equally for this method. Although the modelling approach is flexible and can be made to incorporate various influences of biotic and abiotic variables on disturbance initiation and spread, such dependencies must be parameterized with adequate accuracy to make the modelling approach reliable.

References: Andison (2000); Cumming (2000); Wimberly et al. (2000).

Notes: See notes for Method 2-A.

Group 3: Methods based on record of intervals between consecutive disturbances

Data description: Representative point sample, giving *a sequence of disturbance dates* for each sample point.

Potential scope: Disturbance types for which evidence of a disturbance survives subsequent disturbances and can be used to accurately date past events.

Typical use: Estimate disturbance frequency in a landscape dominated by disturbances of low to mixed severity. Such disturbances tend to leave scars or other marks of repeated disturbance on surviving trees. For example, fires of low to mixed severity may scar rather than kill trees with sufficiently thick bark, and patterns of suppression followed by release in radial growth of understorey trees identify certain bark beetle outbreaks. Where no scars or other characteristic marks in the tree ring pattern are available, disturbance dates can often be determined by identifying and aging cohorts that regenerated after previous disturbances. Another source of interval data is soil charcoal records (e.g., Gavin 2000; Hallett et al.2003.).[28]

Corresponding FIP fields or FIP fields that may serve as proxy: N/A.

Other data available in provincial archives:

a. Digital fire atlas, the spatial version of the fire database (see Group 2).
b. CFS pest data archives (see Group 2).[29]

Ideal data collection procedure:

a. Sample a regular grid or random selection of sample plots. Select at least three trees per plot that are likely to have recorded multiple disturbance events in their rings. Use dendrochronological methods to determine disturbance dates. Pool disturbance dates from the sampled trees to establish a complete record of disturbance occurrence for the plot. Ideally, plots should be small, and sampled trees should be as close together as possible, because it is assumed that all sample trees have experienced the same disturbance history. Additional recommended procedure: Sample multiple recorder trees to compensate for failure to record disturbance events. Oversampling and/or simulation modelling are also recommended to establish appropriate sampling rates (see Group 1 notes on suggested data collection procedure for time-since-disturbance data).

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[28] Charcoal records from lake sediments also fall into this category. However, the catchment area that contributes to the input of charcoal into a lake is often too large to allow interpretation of intervals as point intervals. Most lake charcoal records are more properly interpreted as area intervals (i.e., intervals between consecutive events [or episodes of events] occurring at some, not necessarily the same, location in the catchment area).

[29] Conceptually, these two data sources meet the requirements. However, in practice neither the fire atlas nor the pest data typically provide sufficient records of consecutive disturbances to assemble a disturbance interval database.

b. Sample a regular or random grid of sample points for cohorts of trees. The dates of establishment of distinct cohorts of trees within a stand are used as a proxy of disturbance date. This is a useful method when disturbances do not leave an obvious "signature" in tree rings but kill only a portion of the stand. Identifying the exact date of disturbance from remaining and regenerating cohorts is challenging because (1) disturbance-caused establishment must be distinguished from climate-driven establishment; (2) time delays in regeneration are generally unknown; and (3) cohorts may be not be spatially distinct, particularly in the case of overlapping disturbances (Duncan and Stewart 1991; Heyerdahl 1997; Wong 1999). Methods of spatial autocorrelation and statistical procedures for clustering groups of similar data can help to deal with overlapping events (see Duncan and Stewart 1991).

Analysis Methods:

Method 3-A: Mean disturbance interval from pooled interval data

Principle: Disturbance *intervals* (not disturbance dates) obtained from individual plots are pooled to obtain a disturbance interval distribution for the study area. Properties of this distribution, such as the mean and variance, can then be analyzed. As a further step to allow more formal statistical treatment and test formal hypotheses about disturbance regimes, a mathematical model of disturbance occurrence can be used and an expected shape for the disturbance interval distribution from this model can be derived (see Method 1-A). As in Method 1-A, proceed by fitting the function describing the expected distribution to the observed data, except that in this case the data are the disturbance interval distributions rather than the standing age distributions. Mean disturbance interval, or point disturbance frequency, is then derived as the mean of the fitted distribution.

Assumptions: Spatial homogeneity and stationarity. However, interval distributions can easily be constructed for separate time periods and/or stratified by spatial units to test these assumptions.

Strengths: Allows integration of multiple samples with low information content into a more robust combined record of disturbance dynamics. Analysis of the disturbance interval distribution also makes it possible to estimate characteristics of the disturbance regime other than disturbance frequency, such as risk of future disturbance as a function of time elapsed since the last disturbance event. Easily accommodates spatial or temporal partitioning of the disturbance record to test hypotheses about changes in disturbance dynamics.

Limitations: The method assumes complete recording of disturbances and does not account for variations in disturbance intensity (which may lead to substantial differences in recording probability between sample locations and among different disturbance events). The analysis conducted by Fall (1998) shows that estimates for disturbance frequency obtained using Methods 3-A or 3-B are very sensitive to unrecorded disturbance events. Further work (Fall et al., in prep.) suggests that recording rates for individual fire-scarred trees may be substantially lower than 100%. Hence, multiple trees should be sampled per plot, and trees selected in a way that the entire period of disturbance record is covered by a sufficient number of recording trees. If disturbance dates are obtained from scarred trees, mark-recapture statistics can be used within the framework of a pilot analysis to estimate the proportion of missed disturbance dates per site for the proposed sampling scheme. This information can then be used to determine the number of scarred trees that should be sampled to achieve a sufficiently complete record of disturbance events.

References: Van Wagner (1978); Agee (1993); Johnson and Gutsell (1994); Grissino-Mayer (1995); Heyerdahl and Agee (1996); Fall (1998).

Notes:

a. Before the statistical analysis begins, a "period of reliability" should be established (i.e., the disturbance history record should be truncated to eliminate periods for which it cannot be assumed that all disturbance events occurring at one or more sampling plots were necessarily registered at those plots).

b. Disturbance dates from several sources (e.g., cohort origin dates and fire scar dates) may be integrated to get a complete list of disturbance dates for a stand.

c. Ideally, the computation of point frequency would be done separately for each sampling point, because this removes the assumption of spatial homogeneity and provides a spatially explicit representation of site-specific disturbance frequency (see Method 3-B). However, in practice, individual sampling points often do not offer enough recorded intervals for this approach.

d. When pooling data across sample points, intervals rather than disturbance dates should preferably be pooled. Pooling disturbance dates results in a dataset that can be used only to reconstruct the time between consecutive disturbances occurring anywhere in the study area (area frequency). However, area frequency as a measure of disturbance frequency depends on the size of the study area and hence is of limited generality, unless accompanied by a description of the disturbance size distribution. Thus, if disturbance dates are pooled, the distribution of disturbance sizes should be estimated, and, if possible, a disturbance interval that is independent of study area size should be estimated by using methods from Group 2.

Method 3-B: Disturbance frequency from the interval distribution on a site

Principle: Calculate disturbance frequency as the number of recorded disturbance events experienced by a site over the period of record and/or assemble a distribution of disturbance intervals for a given site and analyze its properties. Results can then be compared and aggregated across sites to obtain a description of disturbance dynamics on the landscape scale.

Assumptions: Similar to Method 3-A, but 3-B does not assume spatial homogeneity.

Strengths: Very simple and direct, requires a minimum of underlying assumptions.

Limitations: Applicable only if individual sample points yield numerous intervals.

References: Kilgore and Taylor (1979); Fall (1998).

Method 3-C: Reconstruct maps of disturbance extent for individual disturbance years

Principle: Use a rule-based algorithm to reconstruct a spatially explicit map of each disturbance event by interpolating disturbance boundaries between sample locations. Alternatively, use existing maps, such as the fire atlas. Superimpose a grid, treat each grid cell as a sample plot, and calculate disturbance intervals using Method 3-A or 3-B, or calculate disturbance frequency as total area disturbed over total period of record (see Method 2-A).

Assumptions: The grid resolution of sample points captures all disturbance events. If violated, this can be addressed by allowing interpolation schemes to take into account the possibility of incomplete records.

Strengths: Simple and very direct. A complete atlas of all historical disturbance events is the ideal dataset to draw inferences about disturbance regime.

Limitations: Results depend on the interpolation scheme (Heyerdahl 1997) and alternative schemes should be tested to estimate the effect of choice of interpolation algorithm on the results.

References: Heinselman (1973); Hemstrom and Franklin (1982); Morrison and Swanson (1990); Heyerdahl (1997); Jordan (2002).

Notes: Use with Method 3-A and/or Method 3-B to get two relatively independent estimates of disturbance frequency.

Group 4: Methods based on knowledge of disturbance behavior

Data Description: Dependent on disturbance type. May include various types of weather and/or climate records; maps of topography, geology, soils, vegetation, and cover; quantitative descriptions of different aspects of disturbance behaviour; and forest response.

Potential scope: All disturbances.

Typical use: To obtain information on various aspects of disturbance dynamics.

Corresponding VRI or FIP fields, or fields that may serve as proxy: Depending on the model.

Other data available in provincial archives: Depending on the model.

Analysis Methods:

Method 4-A: Process modelling to derive disturbance regimes

Principle: Uses statistical and/or process-based models to derive disturbance regime properties from baseline parameters, such as climate data and predictions, lightning strike frequency, and fire behaviour. In practice, this requires running Monte Carlo simulations of landscape dynamics using disturbance behaviour models. The key distinction between this method and Method 2-B is that in this case the disturbance model requires as input only information on parameters known to drive disturbance occurrence, rather than actual disturbance records.

Assumptions: Relationships between baseline parameters and the occurrence and behaviour of disturbances are well understood.

Strengths: Especially useful for predicting disturbance dynamics under conditions for which no direct historical precedent exists (e.g., frequency or severity of fire under climate change), and more generally in situations where empirical data are difficult or impossible to obtain. Also helpful for calibrating higher-level models that emulate disturbance dynamics (see Method 2-B) and for testing current scientific understanding of disturbance behaviour.

Limitations:

a. Scaling problems: most disturbance behaviour models work on very fine scales.

b. A large number of data, which does not exist for most forest types, is required to parameterize the models. This is a serious concern because errors can accumulate and propagate, and the possibility for testing and verification is limited.

References: Shugart (1987); Keane et al. (1996); Cumming and Wong (2002).

Group 5: Methods based on spatial and/or temporal attributes of canopy gaps

Data description: Proportion of stand/landscape in canopy gaps, approximate date of gap creation, and age of trees filling in gap.

Potential scope: Gap disturbances, such as root rot, endemic windthrow, or snow damage.

Typical use: Gap disturbances in ecosystems infrequently disturbed by stand-replacing events.

Corresponding VRI or FIP fields, or fields that may serve as proxy: Attributes that indicate the amount of horizontal or vertical complexity of the stand; estimates of percent disturbed.

Other data available in provincial archives: N/A.

Ideal data collection procedure:

a. Identify canopy gaps from air photos or stem maps (if dead trees were mapped) and determine the proportion of area in canopy gaps relative to the study area.

b. Use a regular grid or random sampling strategy. In each plot, determine the area of the canopy gap (using field methods or hemispherical photography) and cause of the gap's presence (e.g., edaphic, root rot, windthrow). The time it takes to fill in a gap can be estimated from the date of when gaps were created (dating patterns of tree ring release in understorey or neighbouring trees and/or cross dating the death date of the gapmaker) and the age of trees filling in the gap.

Analysis Methods:

Method 5-A: Turnover time of forests with canopy gaps

Principle: Turnover time equals the time to fill in the gap divided by the percent area in canopy gap.

Assumptions: Amount of gap in the forest is at steady state (e.g., rare influence of large stand-replacing disturbances in these ecosystems).

Strength: Relatively simple calculations.

Limitations: Generally requires intensive fine-scale field sampling and dendrochronological analyses.

References: Lorimer and Frelich (1989); Lertzman and Krebs (1991); Lertzman et al. (1996).

Group 6: Methods based on no or very limited primary data

Data description: No adequate disturbance or proxy data for area of interest are available but data or disturbance parameters have been determined for other areas in similar ecosystems.

Potential scope: All disturbances.

Typical use: To obtain initial estimates of disturbance parameters and aid immediate decisions (e.g., landscape-level planning). As preparation for an in-depth study of disturbance history, to obtain the basic understanding of disturbance dynamics in the area necessary for selecting an appropriate methodology.

Corresponding FIP fields or FIP fields that may serve as proxy: N/A.

Other data available in provincial archives: N/A.

Ideal data collection procedure:

a. Literature review: Data or calculated disturbance parameters from other areas can be used to derive initial estimates if study locations are ecologically, climatically, and physiographically similar. Characteristics of study sites and other areas can be formally compared using a table.

Analysis Methods:

Method 6-A: Synthesis of relevant publications

Principle: If data are available from other sites, use the appropriate analytical method as described above on the data. If disturbance parameters have already been calculated for other sites, determine how these might differ between studies or sites and how this might reflect on disturbances in the area of interest.

Assumptions: Disturbances act similarly in different locations.
Strengths: Inexpensive.
Limitations: Suitable reference studies may not always be available. Because of the variability in disturbance regimes, estimates derived from other locations must be used with caution.
References: Wong (2000); Dorner and Wong (2002).
Notes: A literature review of disturbances in other similar ecosystems can help determine whether estimates derived from all the above methods are within ranges determined elsewhere. If they are not, then a field-based study may be required.

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3 APPLICATION EXAMPLE—A QUANTITATIVE RECONSTRUCTION OF DISTURBANCE FREQUENCY BY BEC VARIANT IN THE ARROW FOREST DISTRICT

Brigitte Dorner, Holger Sandmann, and Carmen Wong

3.1 Introduction

In this part of the report, we use current forest inventory and environmental data of the Arrow Forest District to reconstruct changes in disturbance return intervals between 1700 and 2000. Our spatial units of analysis are seven variants of the Interior Cedar–Hemlock and Engelmann Spruce–Subalpine Fir biogeoclimatic zones occurring in the Arrow Forest District. While we are using real-world data, our emphasis in this section is on the technical and applied aspects of preparing the data, undertaking the quantitative analyses, and structuring and interpreting the large volume of output. Our intent is to provide anyone interested in the quantitative reconstruction of natural disturbance dynamics with a detailed account of the various procedures and assumptions that need to be taken into consideration whenever Forest Inventory Planning data (FIP) (B.C. Ministry of Forests 1998b) and biogeoclimatic ecological classification data (BEC) (B.C. Ministry of Forests 2001) are used as input sources. Note that an in-depth analysis of the ecological or management-related aspects of the results specific to the Arrow Forest District was outside the scope of this report.

While we present and compare several alternative scenarios about historical disturbance dynamics, all of our results are based on the same empirical procedure, termed the Rollback Method (see Method 1-C, Part 2, this report). In this example, we focus on only one of the methods that potentially might be used with the Arrow Forest District data. We chose the Rollback Method because we consider it to be the best analytical procedure for our task. It combines the least restrictive set of analytical assumptions with the ability to gain knowledge about the temporal variability in disturbance rates and the historical range of variability in seral stage distribution.

This part of the report follows the logical steps of undertaking a complex analysis of this type (see also Part 2, this report): evaluating and preparing the input data, choosing an appropriate analysis method, developing procedures and scenarios to address uncertainties about the input data as well as the ecological dynamics of the study area, and presenting and interpreting the output.

3.2 Arrow Forest District: Study Area and Data Sources

The Arrow Forest District in southeastern British Columbia extends from the Selkirk Foothills north into the central Columbia Mountains and comprises an area of approximately 700 000 ha. The entire area is hilly or mountainous, but topographic relief is generally steeper and more rugged in the central and northern parts (Figure 3a). The strong elevational gradients, in combination with a north–south precipitation gradient, have led to a wide range of vegetation types: the Arrow Forest District contains 14 biogeoclimatic variants (Figure 3b). Low-elevation areas are dominated by IDF and ICH variants, grading into ESSF variants and alpine tundra at higher elevations. In addition to the Arrow Timber Supply Area (TSA), the Arrow Forest District contains Tree Farm Licence (TFL) 3 and part of TFL 23.

Data Layers Used in Unaltered Form

- FIP database and associated spatial polygon coverage for the Arrow Forest District (Arrow TSA, TFL 3, and the part of TFL 23 falling within the forest district boundaries). Spatial data provided in raster format, cell resolution 50 × 50 m.
- Summarized audit plot data for the Arrow TSA, TFL 3, and TFL 23.
- Biogeoclimatic variants. Data supplied in raster format, cell resolution 50 × 50 m.
- Subsection of provincial fire database, including all ignitions recorded for the Arrow Forest District between 1950 and 1997.

Data Layers that Were Changed or Adjusted before Analysis

We used Blackland GRASS Version 1.992 and Microsoft EXCEL 2000 to prepare the FIP data for analysis. Statistical analyses were performed using custom software implemented in SPLUS 5.0 and SPLUS 6.0.

- FIP data were checked for internal consistency, and stand age was determined from a comparison of projected FIP age and year of last disturbance (where available), according to the procedure described in Appendix I in Dorner (2001).
- FIP polygons and biogeoclimatic classification

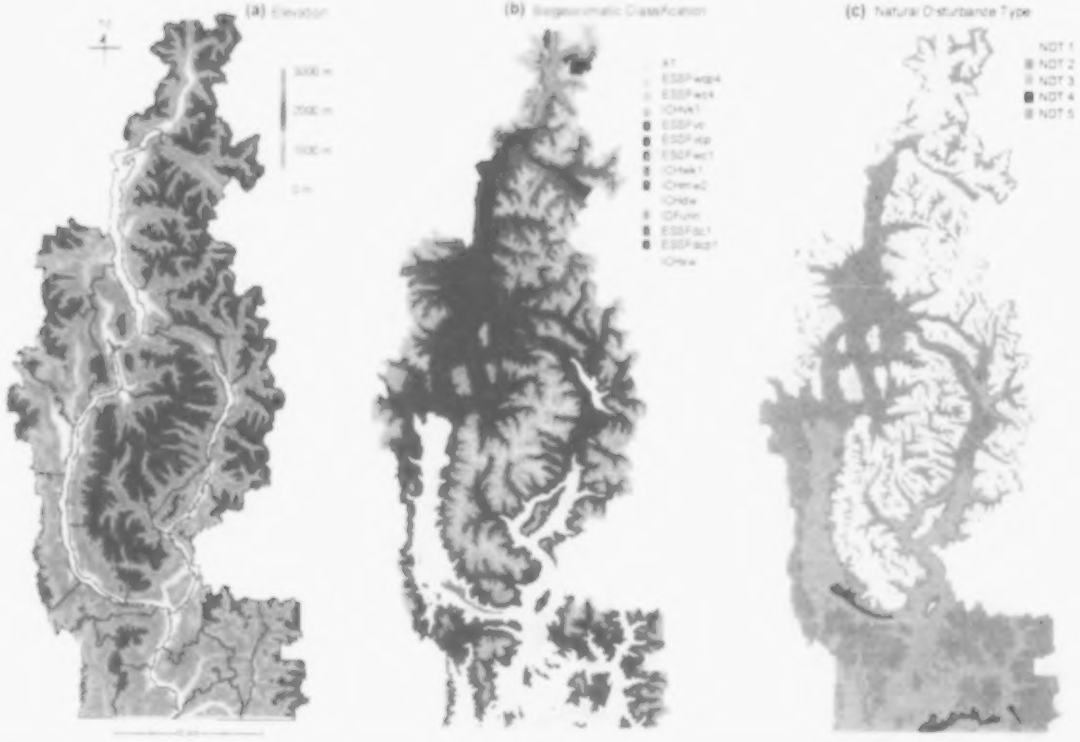

FIGURE 3 *Arrow Forest District: (a) digital elevation model, with landscape unit boundaries and lakeshores outlined in black; (b) biogeoclimatic variants; (c) natural disturbance types*

were overlaid in GRASS GIS to obtain biogeoclimatic information for the FIP data. FIP polygons crossing biogeoclimatic boundaries were split as necessary in this process.

- Polygon centre points from the fire database were converted to UTM and imported to GRASS GIS to obtain biogeoclimatic variants for each fire polygon.

Assessment of Existing Knowledge about Disturbance Dynamics in the Study Area

Current knowledge about disturbance dynamics in the ICH and ESSF is summarized in Part 1 of this report and therefore not repeated here.

Analysis of Existing Data on Disturbance Dynamics: British Columbia Fire Atlas

To estimate fire frequency from the fire atlas data, we tallied up total proportion of area burned in fires that ignited within the study area during the study period (1950–1997) (Method 2-A, this report). This method produces potentially incomplete results because it does not account for fires burning outside the study area, or for fires that ignited outside the study area and burned into the study area.

Fire frequencies determined from the fire atlas data are magnitudes lower than the pre-1950 disturbance frequencies estimated from the standing age distribution (compare results in Table 2 with the summary sheets for the individual variants in Section 3.6). The extremely long return intervals suggest either that the recent fire regime has been substantially affected by fire suppression and fire exclusion, or that the fire regime in the area is dominated by relatively rare, large fire events (none of which occurred during the relatively short period of observation). In either case, we conclude that the fire atlas data are probably incomplete and not representative of the full range of historical fire dynamics. A more detailed analysis of the fire atlas data using Method 2-B (Part 2, this report) seemed unlikely to provide additional insights into historical disturbance dynamics.

TABLE 2 *Mean disturbance return interval for the period 1950–2000 as determined from the fire atlas data*

		Period 1950–1997			Period 1960[a]–1997		
Biogeoclimatic variant	Total area in variant (ha)	Area burned by lightning fires started in variant (ha)	Annual proportion of area burned by fires started in variant (%)	Corresp. disturbance return interval (yr)	Area burned by lightning fires started in variant (ha)	Annual proportion of area burned by fires started in variant (%)	Corresp. disturbance return interval (yr)
AT	24 915	2.1	0.0002	569 474	2.1	0.0002	450 834
ESSFdc1/dcp1	4 348	0.9	0.0004	231 907	0.5	0.0003	330 467
ESSFvc/vcp	4 998	0.1	0.00004	2 398 800	0.1	0.0001	1 899 050
ESSFwc1	136 839	1390.1	0.0212	4 725	1383.6	0.0266	3 758
ESSFwc4	337 417	6805.8	0.0420	2 380	5 786.7	0.0451	2 216
ESSFwcp4	98 989	193.7	0.0041	24 530	192.4	0.0051	19 551
ICHdw	243 028	2 588.0	0.0222	4 507	2 530.6	0.0274	3 649
ICHmw2	454 059	9441.0	0.0433	2 309	8 248.6	0.0478	2 092
ICHvk1	19 347	1575.8	0.1697	589	964.8	0.1312	762
ICHwk1	52 078	2595.5	0.1038	963	2003.4	0.1012	988
ICHxw	7 906	5.1	0.0013	74 407	4.6	0.0015	65 308
IDFun	4 355	21.9	0.0105	9 544	16.1	0.0097	10 278
Total	**1 388 275**	**24620.0**	**0.0369**	**2 707**	**21133.5**	**0.0401**	**2 496**

a Fire atlas data collected before 1960 may be incomplete (see discussion of this data source in Part 2).

3.3 Rationale for Using the Rollback Method

We chose the Rollback Method (Method 1-C, Part 2, this report) for the analysis of the standing age distribution derived from the FIP database based on the following considerations:

- The analysis was to be based primarily on FIP (age) data. Hence, we needed a method that would allow us to derive disturbance frequency from time-since-disturbance data.
- Standing age structure in the study area does not exhibit a negative exponential or Weibull shape, a prerequisite for using Method 1-A (histograms of the standing age distribution for all biogeoclimatic variants analyzed are shown in the summary sheets in Section 3.6).
- Anecdotal evidence indicates widespread fires associated with early-settlement activities and railroads (Pat Fields, B.C. Ministry of Forests, Arrow Forest District, pers. comm., 2002). More recently, timber harvesting and disturbance suppression have most likely altered the disturbance dynamics in the area. Hence, it would be unreasonable to assume that disturbance dynamics were stationary during the past.
- Mountain pine beetles are currently at epidemic levels in parts of the study area. Pine beetles and other forest pests may also have played an important role in the historical disturbance dynamics of the area. If so, susceptibility to disturbance may have been dependent on stand age.

In addition to estimates of disturbance rates based on age class rollback we also present, where appropriate, estimates derived using the maximum likelihood estimate (Method 1-B; see Reed et al. 1998).

3.4 Developing an Error Model for FIP Age Data

In the analysis presented here, FIP age (i.e., the database attribute "PROJ_AGE") is used as a proxy for time elapsed since the last stand-replacing disturbance. It is a well known that FIP age, which is largely based on visual interpretation of aerial photography, is less accurate as a predictor of time elapsed since last disturbance than, for example, estimates based on tree ring counts and fire scar dates (e.g., Pollack et al. 1997; Andison 1999). When using FIP data as an indicator of time since disturbance, the impact of potential inaccuracies in the FIP data on analysis results must therefore be accounted for.

Conceptually, the observed age distribution is a result of adding stochastic error terms to the true time-since-disturbance distribution. To reconstruct the original time-since-disturbance distribution for our analysis, we needed to "subtract" the added error terms from the observed age distribution. Unfortunately, an accurate reconstruction of the original distribution is not possible, because we do not know the size of errors introduced during the air photo interpretation. However, if a sample of more accurate age data (e.g., from tree rings in sample plots) is available, we can use observed discrepancies between FIP age and ground age to parameterize a stochastic model of FIP error. This model can then be used to reconstruct a set of samples of time-since-disturbance data, each of which may have given rise to the observed age distribution.

We identified three aspects of FIP error of concern in this analysis. The first is systematic bias in FIP age (i.e., a consistent tendency to over- or underestimate time elapsed since last disturbance). The second aspect is non-systematic error in FIP age estimates around the date of true stand age. The third aspect is related to the origin of clusters found in the FIP age distribution and the type of historical disturbance dynamics in the area. In the following, we describe the development and implementation of a statistical model of FIP error that addresses each of these concerns.

Errors in FIP Stand Age Estimates I: Systematic Bias

Two sources of systematic bias are considered in this study. The first occurs because FIP age is intended to represent the mean age of a stand's dominant/codominant layer,[30] rather than stand age in the sense of time elapsed since the last stand-replacing disturbance. Discrepancies between the two interpretations of stand age arise because seedlings may take years to decades to establish after a major disturbance event (e.g., Parish et al. 1999). In addition, the codominants are not necessarily the oldest trees in the stand. More significantly, any estimator based on tree age may be misleading if tree regeneration is not indicative of a stand-replacing disturbance event, or if a stand's "true age" exceeds the lifespan of the leading tree species.[31] This last issue is best addressed by (1) limiting analyses of stand age to areas where stands are primarily even-aged and stand-replacing disturbances are known to be a dominant agent of stand renewal; and (2) limiting analysis to a time period not exceeding the typical lifespan of the leading species.

Regeneration delay was addressed by comparing estimates of stand age to estimates of disturbance year for those FIP database entries for which PROJ_AGE and ACT_YEAR[32] attributes were available. Entries were considered consistent and included in the analysis only if time since disturbance was greater or equal to PROJ_AGE, and PROJ_AGE was within 50 years of time since disturbance.[33] Median values for regeneration delay are 10 years after fire and 3 years after logging (see Dorner 2001). In other words, FIP age underestimates time since disturbance by 10 and 3 years, respectively.

The second potential source of systematic bias is systematic under- or overestimation by the photo interpreter of the codominants' mean age. To determine the size of this type of bias, we compared FIP age estimates to true stand age reported for audit plots, the latter being obtained from tree ring counts (B.C. Ministry of Forests 1998a) (Figure 4). Bias was calculated as FIP age less audit plot age. Average bias was 11.5 years for all stands combined, and 20.4 years when only stands labelled older than 100 years in either the FIP data or the audit plot data were considered. Corresponding median bias was 3 years and 15 years, respectively. Thus, if the audit plot data are assumed to be correct, FIP age overestimates true stand age by somewhere between 3 and 20 years.

The estimates of bias due to regeneration delay and photo interpretation error can be combined in different ways into an overall estimate of FIP age bias, depending on one's confidence in the reliability of the disturbance date (ACT_YEAR) recorded in the FIP data. First, assume that the information about disturbance year provided in the FIP ACT_YEAR is accurate, and that the estimates of regeneration delay calculated above are reliable. Because the audit plot data indicate that the true stand age is typically less than the FIP age data would suggest, the actual regeneration delay should then be between 3 and 20 years longer than the 3 and 10 years originally estimated from the comparison of ACT_YEAR and FIP age. However, since we are using FIP age rather than audit plot age, the estimate of total bias is equivalent to the original estimate for regeneration delay (i.e., FIP age underestimates time since disturbance by 10 years for natural disturbance and 3 years for logging). Alternatively, we may distrust the reliability of the FIP ACT_YEAR attribute because of the general uncertainty inherent in air photo interpretation. In this case, we do not have any reliable information on regeneration delay. However, since the presence of regeneration delay implies that stand age underestimates (rather than overestimates) time since disturbance, we know that the bias introduced by photo interpretation error and the bias introduced by regeneration delay have opposite signs and therefore somewhat cancel each other. Thus, unless true regeneration delay is substantially greater than a decade, the size of the systematic bias in FIP age estimates should be approximately ±10 years.

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[30] Definition: "Age is an average age, weighted by basal area, of the dominant, codominant and high intermediate trees for the leading and second species of each tree layer identified." (B.C. Ministry of Forests 2000, Section 6.6).

[31] Using FIP age as time-since-disturbance data assumes that each FIP polygon represents a stand that underwent renewal after catastrophic disturbance. For some of the wettest (ESSFvc/wc) and driest (IDF) ecosystem types in the Arrow Forest District, this assumption may not hold (e.g., Antos and Parish 2002). Instead, forest dynamics may have been governed by fine-scale disturbances and mortality for a very long time and most or all of the trees are younger than the time since the last stand-initiating disturbance.

[32] Where available, the forest inventory database records information on occurrence of natural disturbance, salvage, and/or harvesting operations, as well as silvicultural treatments. For each of these "activities" affecting a polygon, the date and type of the activity is recorded in a pair of fields labelled ACT_YEAR and ACT_CD. To investigate regeneration delay, we selected polygons for which a wildfire disturbance was recorded.

[33] Computed from 1999 data as (99 - ACT_YEAR) ≥ PROJ_AGE ≥ ((99 - ACT_YEAR) - 50).

In pilot analyses, inclusion of a positive or negative bias term of 10 years changed disturbance interval estimates by approximately 10–20 years. However, inclusion of a constant bias term creates problems for the following analysis of disturbance rates because it shifts the minimum age represented in the age distribution. For instance, a negative bias of 10 years shifts the minimum age represented from 0 to 10 years, resulting in distorted estimates of disturbance rates for the most recent time period. Because an error of up to two decades is relatively insignificant compared with the overall uncertainty inherent in the scenarios (see below), we decided *not* to include a bias term into the FIP error model used for the analysis presented below.

Errors in FIP Stand Age Estimates II: Variability around True Age

Error in FIP age is a concern even if there is no substantial systematic bias. FIP age errors can obscure patterns and trends visible in the age distribution and make it difficult to accurately estimate disturbance rates for particular time periods. To quantify the distribution of FIP age around true stand age, we determined the distribution of error terms calculated as FIP age minus true stand age. Again, true stand age was taken from audit plot data. Diagnostic scatter plots show that error in FIP age increases with stand age (Figure 4). To allow us to compare FIP error terms across different stand ages, we scaled error terms by stand age (Figure 5). Except for a few outliers, this transformation causes errors to be approximately normally distributed, with similar variance across the entire age spectrum (Figures 5 and 6). Hence, scaled FIP error was modelled as a normal distribution, with standard deviation $\sigma = 0.35$ estimated from the data (Figure 6, right panel). Consistent with our decision to disregard the small systematic FIP bias, the mean of the distribution was set to zero.

Errors in FIP Stand Age Estimates III: Clusters in the Age Distribution

FIP ages show some clustering around specific age values, most notably at ~220 years and ~320 years projected age (Figure 7). The presence of such clus-

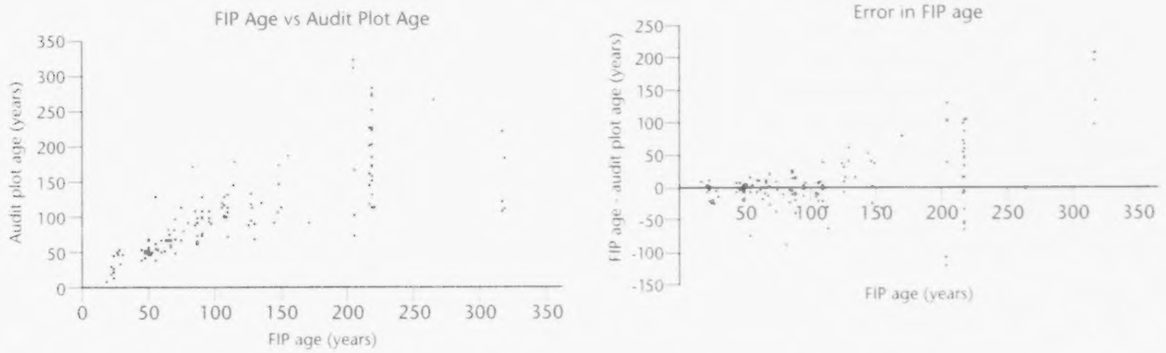

FIGURE 4 *Relationship between FIP age and Audit Plot age and difference between FIP age and Audit Plot age (FIP error).*

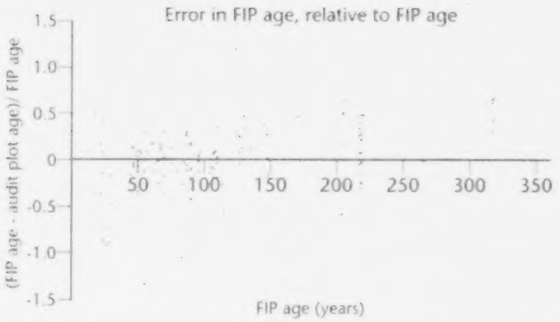

FIGURE 5 *FIP error, scaled by FIP age data. Positive values indicate underestimation of true stand age, negative numbers indicate overestimation.*

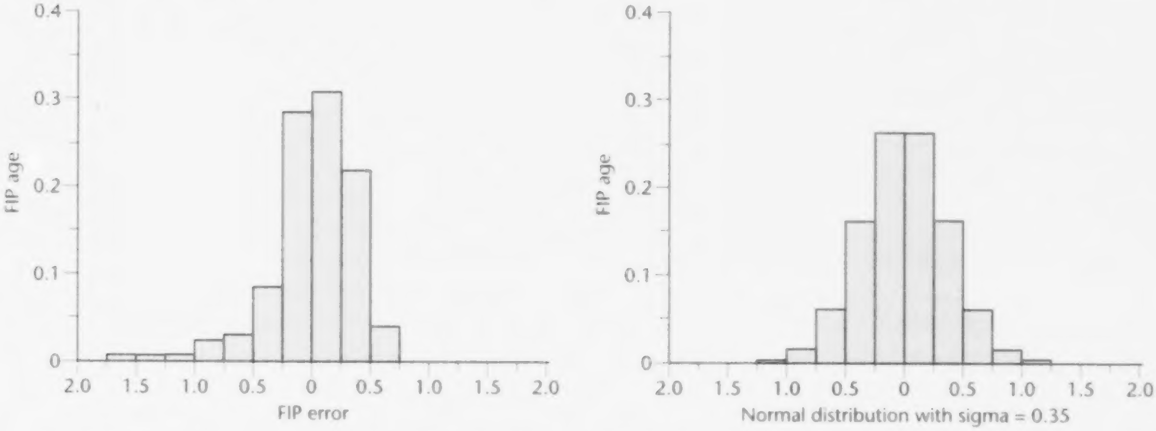

FIGURE 6 *Distribution of errors in FIP age data scaled by FIP age (left; see also Figure 5), and normal distribution used to model these errors (right).*

ters in forest age structure, if real, would indicate pulses of stand establishment following large, episodic disturbance events, such as climate-driven fire episodes and/or outbreaks of mountain pine beetle or other forest pests. However, many of the clusters coincide with midpoints of the age classes used historically for forest inventory. During the transition from age-class to age-based interpretation standards, class midpoints were commonly used instead of age estimates (M. Eng, B.C. Ministry of Forests, Research Branch, pers. comm., 2002). Thus, many of the clusters may simply be artifacts of former interpretation standards. If this were the case, clusters around midpoint values would suggest that little is known about the actual distribution of polygon ages beyond the fact that they were originally placed into the 140–250 years and the 250+ age groups. Within these broad age classes, total area may thus have been distributed evenly across the set of years comprising the age class, or alternatively, in large clusters similar to those observed in the actual FIP age distribution (though not necessarily around the same age values).

The comparison of FIP age and audit plot age (Figure 4) shows a wide range of audit plot ages for FIP polygons that are part of the clusters at ~220 years and ~320 years, respectively. Thus, stand age in the oldest age groups appears to be somewhat more evenly distributed than the FIP data would suggest. However, only a small percentage of the FIP polygons is represented in the audit plot data, and audit plot age does not account for regeneration delay and thus does not necessarily reflect stand establishment dates very accurately (B.C. Ministry of Forests 1998a). Hence, it is difficult to draw conclusions regarding

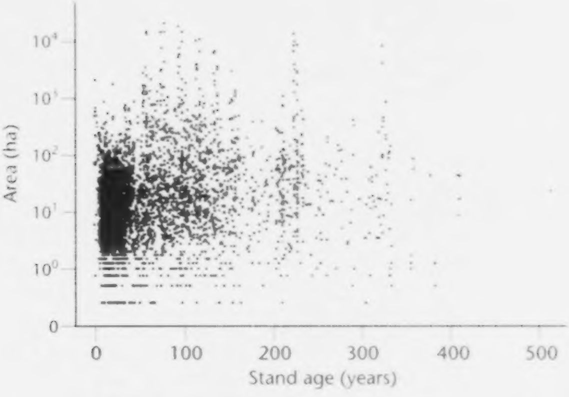

FIGURE 7 *Stand age vs. polygon area for FIP polygons in the Arrow TSA.*

the nature of clusters in the FIP age distribution from this analysis. On the other hand, disturbance regimes in which rare, large disturbance episodes alternate with extended periods of low disturbance occurrence have been documented for many areas, including nearby wilderness areas in the United States and Canada (e.g., Lehmkuhl et al. 1994; Van Wagner 1995; Barrett et al. 1997; Rollins 1999). In general, mounting scientific evidence shows that episodic disturbance regimes and the resulting highly variable standing age distributions are the rule, rather than the exception for many forest ecosystems (e.g., Baker 1992; Boychuk and Perera 1997; Armstrong 1999). Consequently, we included both models of disturbance dynamics—infrequent large disturbances and predominantly small disturbances dispersed in time—in our analyses.

Final Choice of FIP Error Models

Based on our assessment of error in FIP age data described above, we modelled the cumulative impact of FIP errors in our analyses of historic disturbance dynamics by adding error terms to the raw FIP age. Our goal was to generate a series of hypothetical time-since-disturbance data that could all equally likely have given rise to the observed FIP data. These "alternative realities" were then used throughout the analysis to produce a range of values for disturbance rate, which reflects the uncertainty introduced by uncertainties in FIP age.

As indicated above, FIP errors increase proportionally with stand age and are approximately normally distributed, with little or no significant bias. Accordingly, we calculated error terms for the various FIP polygons by drawing from a normal distribution with a mean of zero and standard deviation $\sigma = 0.35$. The scaled error terms thus obtained were then multiplied by FIP age and added to the age currently assigned to the polygon (see also B.C. Ministry of Forests 1999).

The two different assumptions about historical disturbance dynamics, large episodes versus a dispersed regime, are reflected in two alternative ways of calculating error terms for FIP polygons with the same age. The assumption that clustering is mainly an artifact of the FIP data was modelled by calculating a separate error term for each FIP polygon (termed *"dispersed FIP error model"*). The assumption that clusters representing large disturbance years are present in the true age distribution was modelled by using the same error term for all polygons with the same FIP age (termed *"aggregated FIP error model"*). We then analyzed for both error models in parallel to estimate the impact that the presence of clusters has on analysis results.

3.5 Alternative Scenarios of Disturbance Dynamics and Logging History

Age structure data generally do not provide sufficient information to allow an unambiguous description of historical disturbance dynamics. For example, it is generally not possible to distinguish between nonstationary disturbance dynamics and age-dependent susceptibility to disturbance (e.g., Reed et al. 1998). The problem is exacerbated by inaccuracies in FIP age and erasure of evidence due to harvesting. As discussed above, we were unable to establish whether the age structure in the study area shows the clusters typical of a highly episodic disturbance regime with associated non-equilibrium age structure. Similarly, pre-harvest age of logged areas is unknown for the Arrow Forest District and the effects of harvesting on the pre-harvest age structure in the study area are therefore difficult to evaluate.

We address uncertainties regarding the nature of historical disturbance dynamics and the impact of timber harvesting by investigating, in parallel, several scenarios that represent alternative assumptions about characteristics of the historical disturbance regime and pre-harvest age of logged areas. Note that not all scenarios are equally likely for all parts of the study area (see Section 3.6). Our main goal in presenting results as alternative scenarios is to illustrate the effect of different sets of assumptions within the framework of a sensitivity analysis (e.g., Haefner 1996). In previous work, we investigated several other factors that could affect the outcome of the analysis, such as potential failure of the FIP data to identify small remnant patches of old forest and spatial variability in susceptibility to disturbance (Dorner 2001, 2002). These analyses are not repeated here because the influence of these factors proved to be of minor significance, compared with the uncertainty introduced by lack of knowledge about natural disturbance dynamics and pre-harvest age of logged areas.

The different assumptions about historical disturbance dynamics are captured in three scenarios:

1. The *Dispersed Scenario* represents a disturbance regime where disturbances are distributed relatively evenly through space and time, a standard assumption in many analyses (see Part 2, this report). If overall disturbance rates are high, the proportion of stands disturbed more than once in any 20-year period will be non-negligible in this case. In addition, this scenario assumes that all stands within a BEC variant are equally susceptible to disturbance, irrespective of their age or position in the landscape. As described above, the Rollback Method reconstructs temporal "snapshots" of historical age distributions in intervals corresponding to the width of one age class. In the dispersed scenario, historical disturbance rates R are calculated from the reconstructed historical age distributions as:

   $$R = -{}^{1}/_{\Delta t} \ln\left(\frac{\sum_{k=1}^{n} A_k}{\sum_{k=0}^{n} A_k}\right)$$

   where Δt corresponds to the width of the youngest age class (20 years in our case) and $A_0 \,..\, A_n$ denote the area of forest in age classes $0 \ldots n$, with 0 the index of the youngest and n the index of the oldest age class (see also Equation [18] in Reed et al. 1998). The assumptions made for the Dispersed Scenario are consistent with those made for the maximum likelihood estimate (Method 2-B, Part 2, this report).
2. The *Episodic Scenario* represents a disturbance regime with large, episodic disturbance events. For this scenario, we assume that we would rarely observe more than one big disturbance episode per 20-year period. Hence, stands are unlikely to burn or be otherwise disturbed more than once per period and it is reasonable to assume that in any given historical time period the area in the youngest 20-year age class represents a fairly accurate estimate of the total area disturbed over the past 20 years. As in the dispersed scenario, we further assume that all stands within a BEC variant are equally susceptible to disturbance, irrespective of their age or position in the landscape. In the episodic scenario, historical disturbance rates R are calculated from the reconstructed historical age distributions as:

   $$R = -{}^{1}/_{\Delta t} \, \frac{A_0}{\sum_{k=0}^{n} A_k}$$

   that is, the proportion of area disturbed during a period is simply the proportion of area in the youngest age class.
3. The *Age-dependent Scenario* represents a disturbance regime in which susceptibility to disturbance is higher for older stands. This scenario was added to capture the type of disturbance dynamics that might be expected in a landscape where bark beetle outbreaks play a significant role. Stands of lodgepole pine become susceptible to beetle attack approximately eight decades after stand establishment (Parminter 1998). Similarly, young stands of spruce are immune to spruce beetle attack until the trees reach a sufficient diameter, which may take up to 70 years. For the Age-dependent Scenario, we therefore assume that stands 80 years or older are the primary target of beetle attack, although younger stands may still be affected by other forms of disturbance, notably fire. Hence, susceptibility to disturbance for the Age-dependent Scenario is modelled as a step function with a 10-fold increase once stands reach 80 years of age. Because we are not aware of any data that quantify age-specific susceptibility for the types of ecosystems in our study area, the factor of 10 is chosen primarily for demonstration. However, the size of increase in hazard with age is consistent with results reported by Clark (1989) for age-dependent susceptibility to fire in mixed-wood temperate forests in Minnesota. While stands within a BEC zone are now differentiated by age, we still assume that the position of a stand in the landscape does not affect susceptibility to disturbance. Although

age-dependent susceptibility could potentially occur in combination with both dispersed and episodic disturbance dynamics, beetle outbreaks are typically episodic phenomena (Drever and Hughes 2001). Thus, we assume episodic dynamics for this scenario to keep the number of alternative scenarios manageable. Historical disturbance rates for this scenario are calculated using the simple ratio formula presented above for the episodic scenario.

Over the past 40 years, the predominant disturbance in the Arrow Forest District was timber harvesting, whereas natural disturbances have played a minor role during this period (Dorner 2001). In our analysis, harvesting dynamics are captured as a distinct disturbance regime with its own characteristic dynamics. For our rollback analyses, we assume that over the last 40 years, the landscape was dominated by this harvesting regime, and susceptibility to disturbance was therefore determined by harvesting preferences. We explore two alternative assumptions about pre-harvest age of logged areas:

1. All stands above minimum harvest age (set to 120 yr) were targeted with equal probability. This is equivalent to assuming that the standing age distribution for stands older than 120 years accurately reflects the relative proportion of stands of different ages removed by harvesting. Unless stands older than harvest age are scattered widely across the landscape, determining the age of harvested polygons from adjacent unharvested areas using a minimum age cutoff should lead to similar results as this "equal probability" scenario for pre-harvest age.
2. Harvesting has preferably targeted older stands. Since it is very unlikely that harvesting would have preferentially targeted younger stands, the equal-probability scenario represents a lower bound on distortion in the age distribution due to harvesting. To counterbalance with an upper bound on harvesting impact, we introduced a scenario where harvested timber comes primarily from the oldest age classes. However, arbitrary assignment of harvested forest (e.g., to age classes beyond 250 yr) would have resulted in distortions to the age distribution and led to spurious "step" effects in the subsequent analysis. To achieve preferential assignment to the oldest age groups we instead used an age-dependent hazard function that implied an exponential increase in susceptibility to harvesting for stands older than 120 years. Thus, relative probability of harvesting was calculated as $2^{AgeClass-6}$.

3.6 Results by BEC Variant

Concepts for Summarizing and Interpreting Different Scenarios

Understanding and interpreting the window into the past provided by the Rollback Method is much like projecting forest dynamics into the future in the Timber Supply Review process. In both cases, inaccuracies in the input data and uncertainty about specific processes require the consideration of several alternative "hypotheses" about forest dynamics throughout the period under investigation. While multiple and (more or less) equally likely scenarios with often wide confidence intervals may not be a desirable outcome of the analysis—given that there was (or will be) only one actual sequence of forest dynamics in a particular area—these results represent the best effort given the current quality of data and our state of knowledge. The challenge, thus, is to present the complex output consistently and transparently. An additional challenge will be to find a meaningful way to interpret the uncertainty inherent in these types of analyses and the degree of variability apparent in natural dynamics within a management context. However, we believe that both a full understanding of the limitations of data source and methods and a clear understanding of the potential range of natural dynamics are important steps towards improving our ability to understand and manage forest ecosystems.

As a result of the various simulations we developed for the Rollback Method, the following datasets were generated:

- For each biogeoclimatic variant, three basic scenarios represent different assumptions about the spatial and temporal dynamics of the disturbance regimes: the *Dispersed Scenario*, the *Episodic Scenario*, and the *Age-dependent Scenario*.
- To explore uncertainties about errors in the FIP age data, each scenario was computed three times: once with the uncorrected FIP age data, once with a correction based on the dispersed error model, and once with a correction based on the aggregated error model.
- To address our lack of knowledge about the age of harvested stands, each of these nine simulations was repeated twice: once with logging of harvestable stands assumed to be independent of age

(i.e., "even logging hazard"), and once with logging assumed to having targeted older stands first (i.e., "exponential logging hazard").

In total, 18 scenarios were analyzed for each biogeoclimatic variant.[34] The raw outputs of each analysis are a reconstructed age-class distribution and rate of disturbance for each 20-year time period. This output was summarized to obtain a description of disturbance dynamics for the "pre-settlement" period (1700–1860).[35] The disturbance rate for the entire pre-settlement period is given as the total proportion of area disturbed during that time period, divided by the number of years in the period. Disturbance rates were converted into return intervals for ease of interpretation. Thus, pre-settlement disturbance interval is simply the inverse of pre-settlement disturbance rate, and estimates of disturbance intervals for individual 20-year periods are simply the inverse of calculated disturbance rate for the period (see Part 2). In addition, the Rollback Method provides the opportunity to track the variability in proportion of forests of specific age classes (e.g., >140 yr) over time. Results for proportions of mature and late-seral forest are not reported in detail here, but can be found in EXCEL spreadsheets available from B. Dorner.

For the 12 scenarios that included one of the two stochastic models of FIP age error, the simulation creating a time-since-disturbance distribution from the observed FIP age distribution was repeated 100 times.[36] Thus, the 100 model runs give 100 estimates of disturbance rate for each 20-year period. Similarly, the model runs provide 100 estimates of pre-settlement disturbance interval. In both cases, the median of the distribution of model results represents our "best guess" of the actual disturbance interval, whereas the spread of the distribution represents our uncertainty about the disturbance interval. We use quantiles of the model results to provide each of the estimates of disturbance rate with confidence intervals (e.g., the lower 5% and upper 95% quantiles of the sample distribution). In the graphs on the summary sheets, these confidence intervals are represented as gray boxes or boxplots around the median.

Change in disturbance rates over time can be considered as having two components: a long-term trend, and short-term variability about this trend. If we assume that the disturbance regime has not changed substantially during the 160 years of the pre-settlement period, variability in disturbance rates between individual 20-year periods during that time can be interpreted as short-term fluctuations around a long-term average (as captured in the pre-settlement disturbance interval). We summarize variability around this average by calculating relative deviation as a percentage of the average. For example, the disturbance rate during a given 20-year period might be two times (or 200% of) the pre-settlement rate, whereas the rate during the following 20-year period might be only 0.25 times (or 25% of) the pre-settlement rate.

The distribution of deviations from the pre-settlement rate informs us about the size of fluctuations we would naturally expect in disturbance rates, or, in other words, about the range of historical variability in 20-year disturbance rates. In the graphs, this historical variability in disturbance rates is shown as two dotted red lines. These indicate the upper and lower limits of the 90% range of fluctuations around the pre-settlement interval (indicated by the red centreline in the graphs). More specifically, if we assume that the red centreline accurately represents the pre-settlement interval, then 90% of the individual 20-year values would have fallen within the bounds determined by the dotted lines.

The range of variability in pre-settlement rates is *not* the confidence interval for the pre-settlement disturbance interval. While the range of variability represents variability in historical disturbance dynamics, the confidence interval merely reflects uncertainty about pre-settlement dynamics arising from uncertainties in FIP age.

While the 18 sets of results may be summarized in many ways in graphs and tables, we present here a systematic approach that intends to achieve consistent and repeatable interpretation by BEC variant. In particular, both ecological and technical aspects of the results are considered in parallel. *Ecological aspects* are the rates of disturbance during a given time period, the change and fluctuation of these rates over time, and the comparison of the former two across biogeoclimatic variants. *Technical aspects* are the uncertainties about the input data as expressed in the alternative scenarios, and the variability (i.e., confidence intervals) associated with each estimate of disturbance rate.

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[34] In addition, and for comparison with the Rollback Method, Reed's MLE (see Method 1-B, Part 2, this report) was computed for each of the three assumptions about FIP age errors.

[35] 1860 was chosen as a cutoff date because it was unclear to what degree activities associated with early European settlement may have influenced fire frequency during the late 19th and early 20th century.

[36] Because the two error models include probabilistic terms, each simulation run will generate different—but equally likely—estimates of historical disturbance rates.

Ideally, local knowledge about ecosystem dynamics would allow the analyst to rank the different scenarios (e.g., from unlikely to likely) and focus on the results of the higher-ranked scenarios. In other cases, the initial number of scenarios might be lower if, for example, the age of harvested patches can be reconstructed with sufficient accuracy. For the Arrow Forest District, no conclusive information exists about the age of harvested stands; thus, data interpretation has to consider both models of logging hazard as equally likely. Likewise, field data are insufficient to choose one FIP error model over the other. However, results obtained from the FIP error models likely present a more accurate representation of historical dynamics than the raw FIP data. Thus, all scenarios based on the raw field data are excluded from the following data interpretation; their results are listed only in the attached EXCEL spreadsheet.

Data Interpretation: Summary Sheets by BEC Variant

In accordance with the general approach taken in this report, disturbance rates were evaluated separately for the different biogeoclimatic variants within the study area. Because of the assumptions and limitations inherent in the Rollback Method and analyses of time-since-disturbance data in general, we restricted our analyses to those variants with a total area within the Arrow Forest District of at least 10 000 ha.

The complete results of all scenarios can be obtained from B. Dorner. We use a four-page template for each variant and interpret the results by focusing on the more likely scenarios in a consistent manner. For each BEC variant, we briefly describe the area in question and show the raw FIP age distribution, which provided the basis for all following analyses. We then present and interpret graphs under three separate aspects:

1. Compare mean disturbance return intervals for the pre-settlement period (1700–1860).
2. Compare confidence intervals for estimates of disturbance return intervals of the pre-settlement period (1700–1860).
3. Compare variability in disturbance return intervals over time, and uncertainty about estimates for each 20-year period between 1700 and 2000.

1. Mean disturbance return intervals for the pre-settlement period (1700–1860).

The graph under this heading gives an overview of the variability in estimated mean disturbance return intervals for the pre-settlement period, computed for the 12 scenarios based on adjusted FIP age data. All scenarios are plotted irrespective of their ranking. The values shown are the median values of the 100 model runs. Graph interpretation: Given the assumptions made in each of the scenarios, this graph represents our best guesses for pre-settlement disturbance intervals.

Under the heading "Interpretation" for this and the other sections of the summary sheets, we briefly list aspects of the data shown in the graphs that would warrant consideration in an in-depth analysis of the ecological and management aspects of the data.

In general, clustering of scenario results should prompt the analyst to gather field or archival data to choose between one or the other assumption. For example, the assumptions made in the age-dependent disturbance model with exponential logging hazard (scenarios labelled M and K, respectively) compound to create a landscape with long return intervals and large amounts of old forest. Obviously, it is of great interest to determine the likelihood that this combination of assumptions represents the respective biogeoclimatic variant.

2. Confidence intervals for estimates of disturbance return intervals of the pre-settlement period (1700–1860).

This section of the summary sheets begins with a summary of current knowledge about historical disturbance dynamics for each BEC variant. To reduce the amount and complexity of the information presented in this and the next section, we focus on only one of the three basic disturbance scenarios—*Dispersed*, *Episodic*, or *Age-dependent*—depending on which one seems most appropriate for the BEC variant under consideration. Because confidence intervals can be computed only for the scenarios that include one of the two stochastic models of FIP error, the graph in this section shows results for four scenarios representing the different assumptions about FIP error and logging history. In a real-world application of this procedure, the choice of most appropriate scenario(s) would probably be based on a consensus of local experts.

The graph in this section repeats the information of the summary graph in the previous section—it shows the pre-settlement return intervals for the chosen subset of four scenarios. In addition, we show 90% confidence intervals as determined by the 5% and 95% quantiles of model results based on 100 runs. Graph interpretation: Because of the uncertainty in the FIP age data, the "best guess" values for disturbance intervals given in the first graph may not be accurate; the wider the bars, the less certain we can be about the true mean. However, we can be reasonably certain that the pre-settlement disturbance intervals fall within the confidence intervals shown in this graph.

3. Variability in disturbance return intervals over time, and uncertainty about estimates for each 20-year period between 1700 and 2000.

The third section of the summary sheets contains four graphs, each one showing, for one scenario, the change of disturbance interval estimates throughout the entire period of analysis. The gray boxplots represent the distribution of the data from the 100 model runs for each 20-year period (the endpoints of the whiskers depict the 5% and 95% quantiles of the sample distribution, the filled boxes represent the central 50% of the distribution). Thus, the median line of each boxplot could be interpreted as our "best-guess" estimate of disturbance interval during that 20-year period, and the width of the boxes and whiskers show the degree of uncertainty associated with individual 20-year period estimates. The graphs also illustrate that this uncertainty increases substantially as we go further back in time.

The "best-guess" interval for the pre-settlement period from the previous graphs is shown as a red horizontal line. It represents the "baseline" estimate for the pre-settlement period against which trends in more recent periods can be compared. The dotted red lines represent the range of variability in pre-settlement disturbance rates.

Conceptually, there is no direct link between the uncertainty in disturbance rates represented by the boxplots and the variability in disturbance rates represented by the dotted red lines. However, high variability in disturbance rates, in combination with uncertainty around age estimates as we would observe under the aggregated model of FIP error, typically leads to greater uncertainty in rate estimates for individual 20-year periods. This is because the uncertainty about FIP age means that big disturbance episodes cannot be clearly assigned to a particular 20-year period. Thus, different model runs create similar patterns of lower 20-year background rates interspersed with peaks corresponding to big disturbance episodes, but the position of the peaks varies from model run to model run. The result is a wide range of rate estimates for the individual periods, because they are interpreted as low-disturbance periods in some scenarios and high-disturbance periods in others. Graph interpretation: The graph shows changes in disturbance frequency over time, against the backdrop of the pre-settlement regime (red centreline = pre-settlement interval, dotted lines = pre-settlement variability in 20-year rates). The gray boxes and whiskers show uncertainty introduced into the individual 20-year estimates by uncertainty in FIP age.

Summary Sheets for ICHdw

The dry warm variant of the Interior Cedar–Hemlock zone (ICHdw) occupies ~243 028 ha of the lower elevations in the Arrow Forest District. It occurs above the IDFun or ICHxw and below the ICHmw2. Forests in this variant consist of a mix of Cw, Hw, Fd, Lw, Pl, Py, and Ep in both climax and seral stands. The *Biodiversity Guidebook* places the ICHdw in NDT3, with frequent stand-initiating events at mean intervals of 150 years.

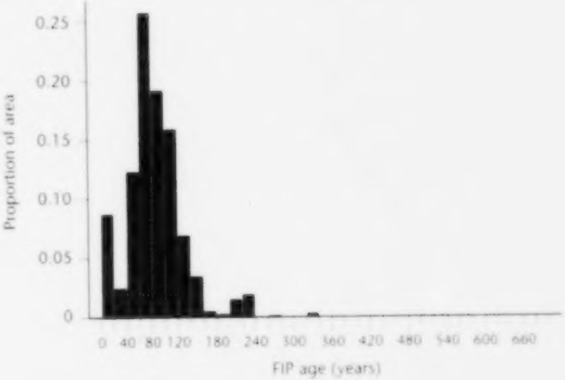


FIGURE 8 *Age distribution for the ICHdw.*

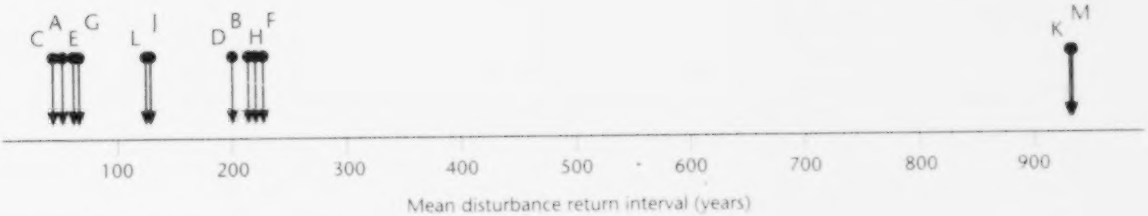


FIGURE 9 *Mean disturbance return intervals (MRI s) for the pre-settlement period (1700–1860).*

Key for Scenarios

- A Dispersed disturbances, dispersed FIP error model, even logging hazard
- B Dispersed disturbances, dispersed FIP error model, exponential logging hazard
- C Dispersed disturbances, aggregated FIP error model, even logging hazard
- D Dispersed disturbances, aggregated FIP error model, exponential logging hazard
- E Episodic disturbances, dispersed FIP error model, even logging hazard
- F Episodic disturbances, dispersed FIP error model, exponential logging hazard
- G Episodic disturbances, aggregated FIP error model, even logging hazard
- H Episodic disturbances, aggregated FIP error model, exponential logging hazard
- J Age-dependent disturbances, dispersed FIP error model, even logging hazard
- K Age-dependent disturbances, dispersed FIP error model, exponential logging hazard
- L Age-dependent disturbances, aggregated FIP error model, even logging hazard
- M Age-dependent disturbances, aggregated FIP error model, exponential logging hazard

Interpretation

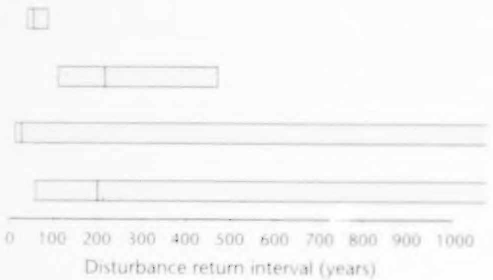
Most influential assumptions: If both disturbances and logging impacted mostly older stands (Scenarios K, M), pre-settlement MRI estimates are much longer than for any of the other scenarios. Therefore, targeted field studies or archival work should try to determine whether these assumptions are reasonable.

Clustering of MRI estimates: Assumptions about the age of stands at the time of harvesting separate MRI estimates into three distinct clusters (in addition to the two "outlier" scenarios). Estimates based on even logging hazard are shorter (~60 yr) than those based on exponential logging hazard (~210 yr), and estimates based on the assumption that natural disturbances impacted mostly older stands are longer than those based on equal probability of disturbance for all stands. Further research should try to acquire data about stand age at logging.

Relation to* Biodiversity Guidebook *(BGB) estimates: The BGB estimate of 150 years is closest to

Scenarios J and L and thus is applicable only if disturbances are age-dependent and logging did not target old stands first. MRI estimates based on even logging hazard (A, C, E, G) are shorter than the BGB estimate, whereas estimates based on exponential hazard (B, D, F, H) are longer.

Similarities with other* BEC *variants: The clustering of MRI estimates, though not necessarily the numerical values, is similar to those for the ICHmw2 and ESSFwc1.



Key for Scenarios

← **ddv** Dispersed disturbances, dispersed FIP error model, even logging hazard (A)

← **ddx** Dispersed disturbances, dispersed FIP error model, exponential logging hazard (B)

← **dav** Dispersed disturbances, aggregated FIP error model, even logging hazard (C)

← **dax** Dispersed disturbances, aggregated FIP error model, exponential logging hazard (D)

FIGURE 10 *Confidence intervals for estimates of disturbance return intervals of the pre-settlement period (1700–1860).*

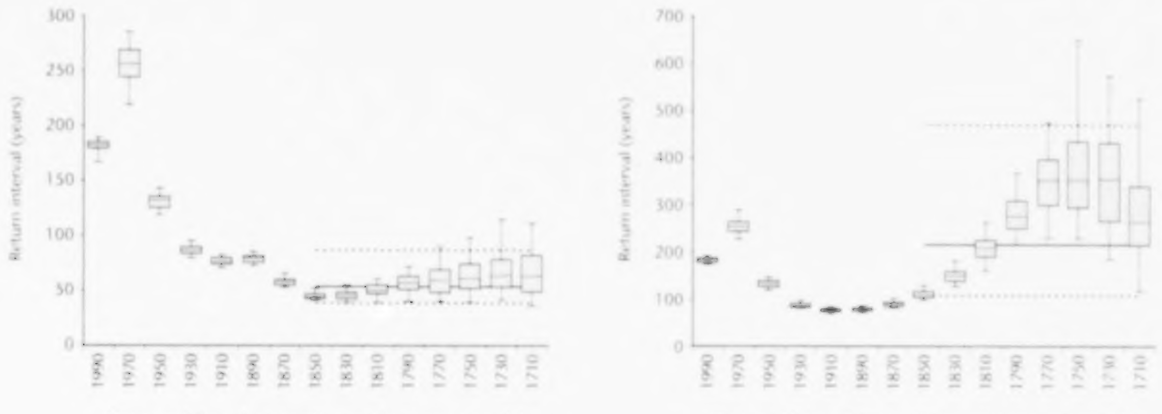
Interpretation

Based on published field studies (see Part 1, this report) and summary information in Braumandl and Curran (editors, 1992), it appears that the historical disturbance regime in the ICHdw included a range of disturbance agents at a range of severities. Therefore, we consider the *Dispersed Scenario* as the best approximation of disturbance dynamics.

Influence of assumptions: The distribution of disturbances over space and time (dispersed vs. aggregated) has a large influence on the confidence intervals around MRI estimates. Therefore, further research should try to resolve whether clusters in the FIP age are artifacts of air photo interpretation.

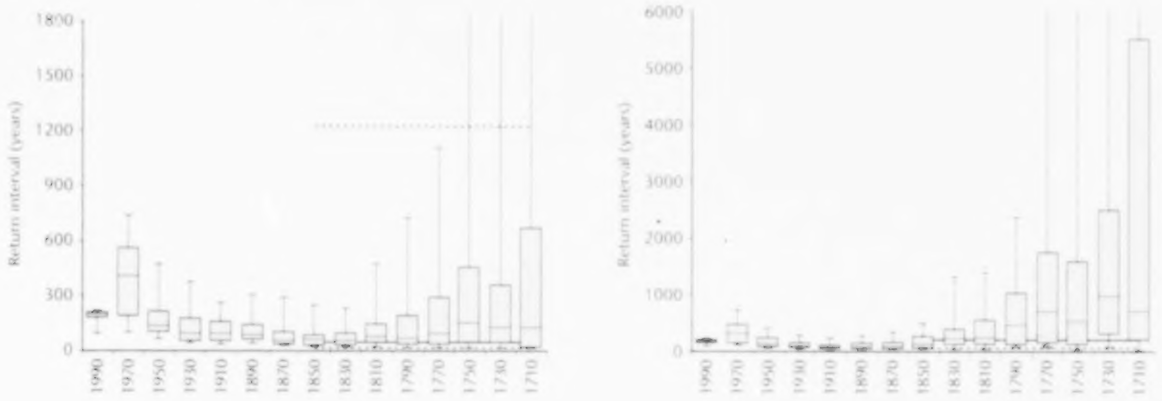
Similarities with other* BEC *variants: BEC variants with similar issues regarding the width of confidence intervals are the ICHwk1, ESSFwc1, ESSFwc4, and ESSFwcp4.

Other observations: Scenarios based on even logging hazard yield the shortest return intervals of all BEC variants included in this study. However, see the note on logging history in the Nelson Forest Region in the next section.



Dispersed disturbances, dispersed FIP error model, even logging hazard

Dispersed disturbances, dispersed FIP error model, exponential logging hazard



Dispersed disturbances, aggregated FIP error model, even logging hazard

Dispersed disturbances, aggregated FIP error model, exponential logging hazard

FIGURE 11 *Variability in disturbance return intervals over time, and uncertainty about estimates for each 20-year period between 1700 and 2000*

Notes: Boxes are bounded by 25% and 75% quartiles and whiskers indicate 5% and 95% quantiles of the data (based on 100 model runs). The solid horizontal line is the mean for the pre-settlement period (1700–1860); dotted horizontal lines indicate the range of variability around this mean (5–95% range). For visual clarity, scales of *y*-axes often differ, and boxes, whiskers, and lines are sometimes clipped.

Interpretation

Influence of assumptions: Assumptions about the age of stands at time of harvesting (left vs. right panels) result in different trends in disturbance return intervals over time. Holt et al. (1999) point out that almost all of the very old ICHdw stands have been harvested in the Nelson Forest Region. If this is true for the Arrow Forest District, scenarios with exponential logging hazard more accurately represent historical dynamics. In fact, even the scenarios with exponential logging hazard might underestimate the length of pre-settlement intervals in this case, because they assume that at least some of the forest in the oldest age classes would have remained unharvested.

Comparison of modern period to pre-settlement period (PSP): If older stands were harvested first (right panels), modern disturbance intervals are similar to estimates for the PSP, following a period of shorter return intervals between 1860 and 1960. On the other hand, scenarios based on even logging hazard (left panels) show increases in disturbance intervals since the PSP; if disturbances were dispersed over time (top left panel), modern disturbance intervals are outside the range of PSP variability.

Comparison to other BEC variants: The only BEC variant with broadly similar trends of variability in disturbance intervals over time is the ICHwk1.

Other observations: Uncertainty generally increases with temporal distance from the present. In addition, scenarios representing large, episodic disturbances (bottom panels) offer less confidence in disturbance return intervals than scenarios with small disturbances scattered more evenly through time (see also Part 2 of this summary sheet).

Summary Sheets for ICHmw2

The Columbia–Shuswap moist warm variant of the Interior Cedar–Hemlock zone (ICHmw2) occupies ~454 058 ha of the lower and mid-elevations in the Arrow Forest District. It occurs above and/or north of the ICHdw and below the ICHwk1 and the ESSFwc variants. Climax zonal sites consist of Cw and Hw, but mixed stands of Fd, Lw, Sxw, Hw, and Cw are more common. Pl, Pw, and Ep occur as minor seral species. The *Biodiversity Guidebook* places the ICHmw2 in NDT 2, with infrequent stand-initiating events at mean intervals of 200 years.

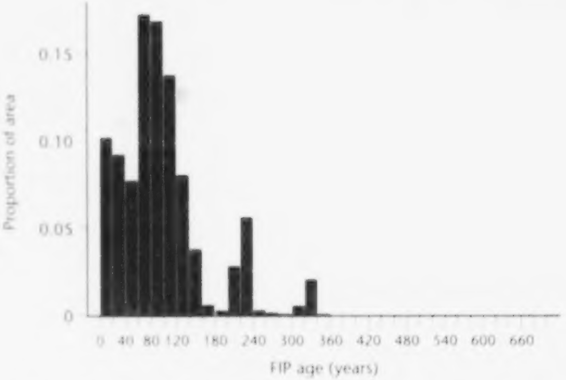


FIGURE 12 *Age distribution for the ICHmw2.*

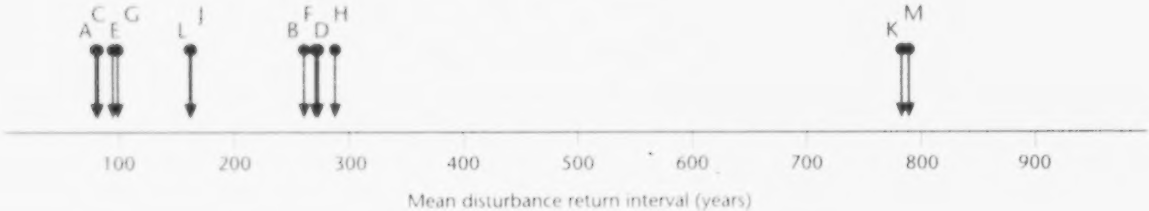


FIGURE 13 *Mean disturbance return intervals (MRIs) for the pre-settlement period (1700–1860).*

Key for Scenarios

A Dispersed disturbances, dispersed FIP error model, even logging hazard

B Dispersed disturbances, dispersed FIP error model, exponential logging hazard

C Dispersed disturbances, aggregated FIP error model, even logging hazard

D Dispersed disturbances, aggregated FIP error model, exponential logging hazard

E Episodic disturbances, dispersed FIP error model, even logging hazard

F Episodic disturbances, dispersed FIP error model, exponential logging hazard

G Episodic disturbances, aggregated FIP error model, even logging hazard

H Episodic disturbances, aggregated FIP error model, exponential logging hazard

J Age-dependent disturbances, dispersed FIP error model, even logging hazard

K Age-dependent disturbances, dispersed FIP error model, exponential logging hazard

L Age-dependent disturbances, aggregated FIP error model, even logging hazard

M Age-dependent disturbances, aggregated FIP error model, exponential logging hazard

Interpretation

Most influential assumptions: If both disturbances and logging impacted mostly older stands (Scenarios K, M), pre-settlement MRI estimates are much longer than for any of the other scenarios. Therefore, targeted field studies or archival work should try to determine whether these assumptions are reasonable.

Clustering of MRI estimates: Assumptions about the age of stands at the time of harvesting separate MRI estimates into three distinct clusters (in addition to the two "outlier" scenarios). Estimates based on even logging hazard are shorter (~90 yr) than those based on exponential logging hazard (~260 yr). Further research should try to acquire data about stand age at logging.

Relation to* Biodiversity Guidebook *(BGB) estimates: The BGB estimate of 200 years falls in the "gap" between estimates based on even logging hazard (Scenarios A, C, E, G, J, L) and those based on exponential hazard (B, D, F, H).

Similarities with other BEC variants: The clustering of MRI estimates, though not necessarily the numerical values, are similar to those for the ICHdw and ESSFwc1.

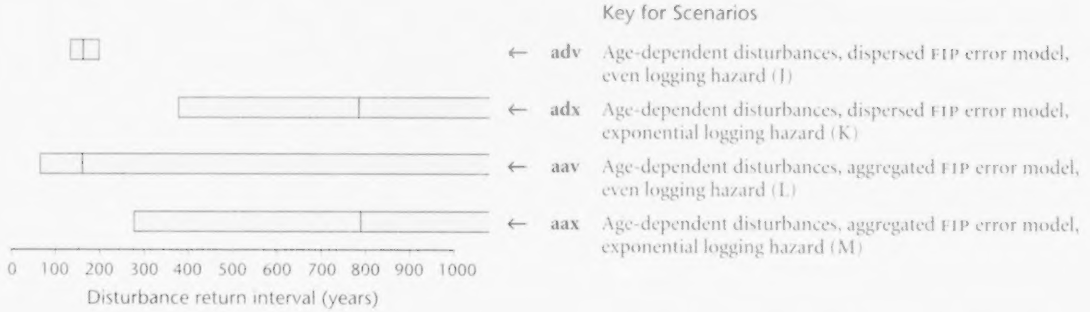


FIGURE 14 *Confidence intervals for estimates of disturbance return intervals of the pre-settlement period (1700–1860).*

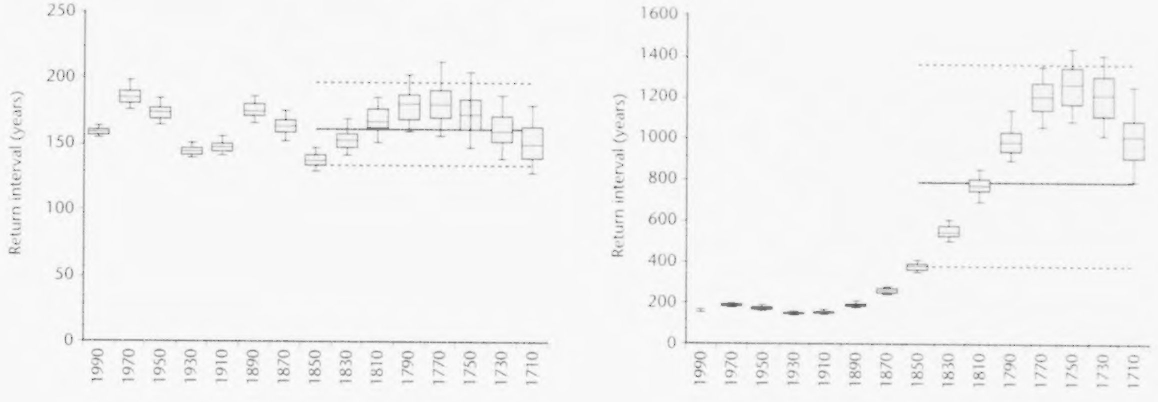
Interpretation

Based on published field studies (see Part 1, this report) and summary information in Braumandl and Curran (editors, 1992), it appears that the historical disturbance regime in the ICHmw2 consisted of episodic stand-replacing events from both fire and bark beetle epidemics. Therefore, we consider the *Age-dependent Scenario* as the best approximation of disturbance dynamics.

Influence of assumptions: The distribution of disturbances over space and time (dispersed vs. aggregated) has a large influence on the confidence intervals around MRI estimates. In addition, the age of stands at time of harvesting has a similar effect for the dispersed scenario (K). Therefore, further research should try to resolve whether clusters in the FIP age are artifacts of air photo interpretation and acquire data about the predominant type of disturbance regime.

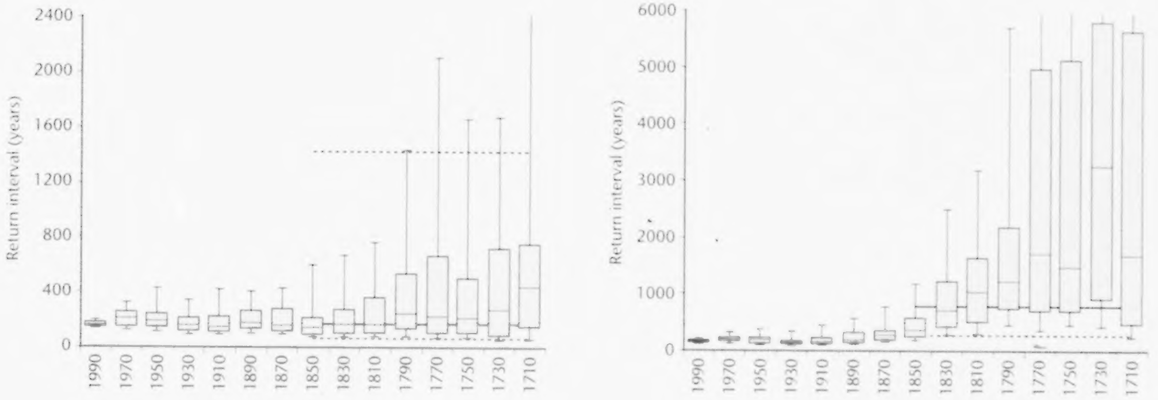
Similarities with other BEC variants: None in this study area.

Other observations: The mean disturbance return intervals of the four scenarios span a wide range (~160–780 yr).



Age-dependent disturbances, dispersed FIP error model, even logging hazard

Age-dependent disturbances, dispersed FIP error model, exponential logging hazard



Age-dependent disturbances, aggregated FIP error model, even logging hazard

Age-dependent disturbances, aggregated FIP error model, exponential logging hazard

FIGURE 15 *Variability in disturbance return intervals over time, and uncertainty about estimates for each 20-year period between 1700 and 2000.*

Notes: Boxes are bounded by 25% and 75% quartiles and whiskers indicate 5% and 95% quantiles of the data (based on 100 model runs). The solid horizontal line is the mean for the pre-settlement period (1700–1860); dotted horizontal lines indicate the range of variability around this mean (5–95% range). For visual clarity, scales of y-axes often differ, and boxes, whiskers, and lines are sometimes clipped.

Interpretation

Influence of assumptions: Assumptions about the age of stands at time of harvesting (left vs. right panels) result in different trends in disturbance return intervals over time but are more pronounced in the years after 1860. Harvesting in the ICHmw2 during the modern period has been extensive, leading to the observed differences. Further research should try to acquire data about stand age at the time of harvesting.

Comparison of modern period to pre-settlement period (PSP): If all harvestable stands were targeted equally (left panels), modern disturbance intervals are similar to estimates for the PSP. On the other hand, scenarios based on exponential logging hazard (right panels) show a marked decrease in disturbance intervals since 1860 and are outside the range of PSP variability

Comparison to other BEC variants: The only other BEC variant with broadly similar trends of variability in disturbance intervals over time is the ESSFwc1. This might be an artifact of choosing the same basic disturbance scenario, but could also be caused by the closeness of the two variants.

Other observations: Uncertainty generally increases with temporal distance from the present. In addition, scenarios representing large, episodic disturbances (bottom panels) offer less confidence in disturbance return intervals than scenarios with small disturbances scattered more evenly through time.

Summary Sheets for ICHwk1

The Wells Gray wet cool variant of the Interior Cedar–Hemlock zone (ICHwk1) occupies ~52 078 ha of the mid-elevations in the Arrow Forest District. It occurs above the ICHmw2 and below the ICHvk1 and ESSFwc variants. Mature forests in this variant consist mostly of Cw and Hw, and Sxw, Pw, Fd, and Bl occur as seral species or minor components. The *Biodiversity Guidebook* places the ICHwk1 in NDT1, with rare stand-initiating events at mean intervals of 250 years.

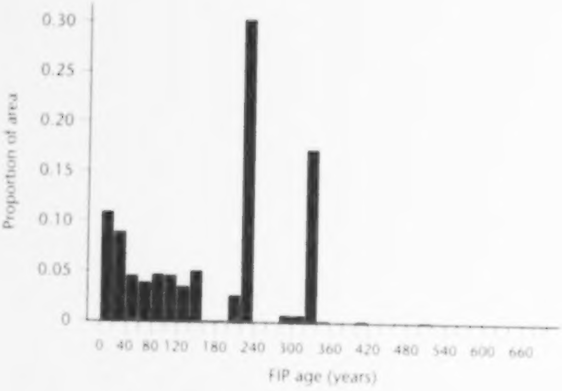


FIGURE 16 *Age distribution for the ICHwk1.*

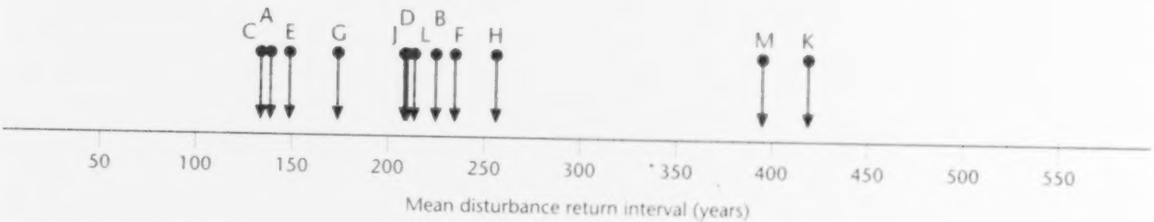


FIGURE 17 *Mean disturbance return intervals (MRIs) for the pre-settlement period (1700–1860).*

Key for Scenarios

- A Dispersed disturbances, dispersed FIP error model, even logging hazard
- B Dispersed disturbances, dispersed FIP error model, exponential logging hazard
- C Dispersed disturbances, aggregated FIP error model, even logging hazard
- D Dispersed disturbances, aggregated FIP error model, exponential logging hazard
- E Episodic disturbances, dispersed FIP error model, even logging hazard
- F Episodic disturbances, dispersed FIP error model, exponential logging hazard
- G Episodic disturbances, aggregated FIP error model, even logging hazard
- H Episodic disturbances, aggregated FIP error model, exponential logging hazard
- J Age-dependent disturbances, dispersed FIP error model, even logging hazard
- K Age-dependent disturbances, dispersed FIP error model, exponential logging hazard
- L Age-dependent disturbances, aggregated FIP error model, even logging hazard
- M Age-dependent disturbances, aggregated FIP error model, exponential logging hazard

Interpretation

Most influential assumptions: If both disturbances and logging impacted mostly older stands (Scenarios K, M), pre-settlement MRI estimates are much longer than for any of the other scenarios. Therefore, targeted field studies or archival work should try to determine whether these assumptions are reasonable.

Clustering of MRI estimates: Different types of assumptions do not result in obvious clusters (other than the two "outlier" scenarios). However, estimates based on even logging hazard are generally shorter (~150 yr) than those based on exponential logging hazard (~230 yr). Further research should try to acquire data about stand age at logging.

Relation to* Biodiversity Guidebook *(BGB) estimates: The BGB estimate of 250 years is longer than that for most scenarios, with the exception of the two scenarios that assume an episodic disturbance regime and exponential logging hazard (Scenarios F, H).

Similarities with other* BEC *variants: The clustering of MRI estimates, though not necessarily the numerical values, are similar to those for the ESSFwc4 and ESSFwcp4.

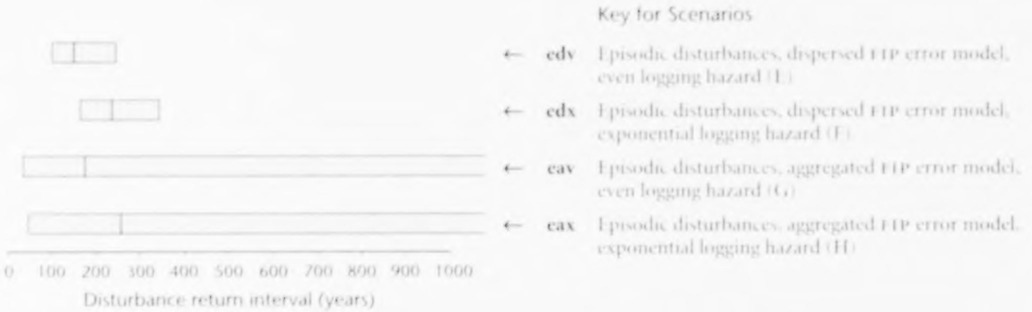


FIGURE 18 *Confidence intervals for estimates of disturbance return intervals of the pre-settlement period (1700–1860).*

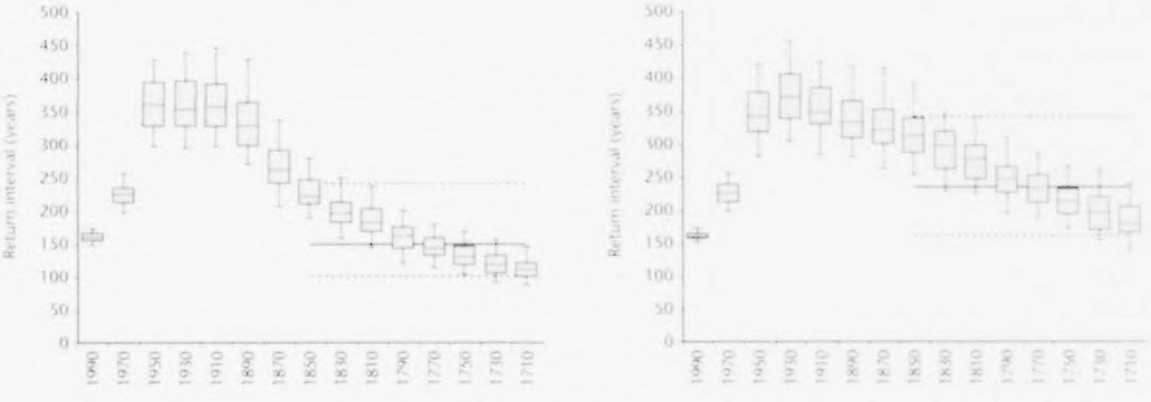
Interpretation

Based on published field studies (see Part 1, this report) and summary information in Braumandl and Curran (editors, 1992), the historical disturbance regime in the ICHwk1 consisted of infrequent stand-replacing events (with very few fires) and small-scale disturbances in between. Therefore, we consider the *Episodic Scenario* as the best approximation of disturbance dynamics.

Influence of assumptions: The distribution of disturbances over space and time (dispersed vs. aggregated) largely influences the confidence intervals around MRI estimates. Therefore, further research should try to resolve whether clusters in the FIP age are artifacts of air photo interpretation.

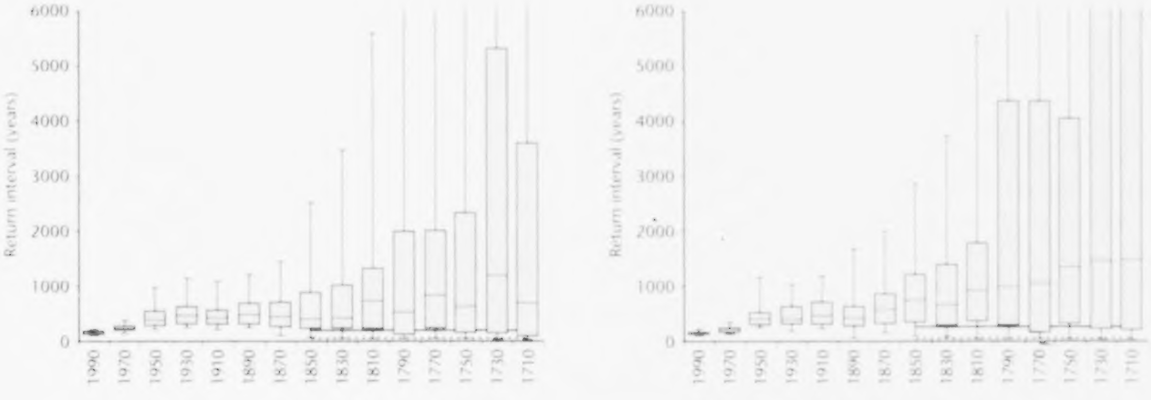
Similarities with other* BEC *variants: BEC variants with similar issues regarding the width of confidence intervals are the ICHdw, ESSFwc1, ESSFwc4, and ESSFwcp4.

Other observations: The range of mean disturbance return intervals for the four scenarios is fairly narrow (140–260 yr).



Episodic disturbances, dispersed FIP error model, even logging hazard

Episodic disturbances, dispersed FIP error model, exponential logging hazard



Episodic disturbances, aggregated FIP error model, even logging hazard

Episodic disturbances, aggregated FIP error model, exponential logging hazard

FIGURE 19 *Variability in disturbance return intervals over time, and uncertainty about estimates for each 20-year period between 1700 and 2000.*

Notes: Boxes are bounded by 25% and 75% quartiles and whiskers indicate 5% and 95% quantiles of the data (based on 100 model runs). The solid horizontal line is the mean for the pre-settlement period (1700–1860); dotted horizontal lines indicate the range of variability around this mean (5–95% range). For visual clarity, scales of y-axes often differ, and boxes, whiskers, and lines are sometimes clipped.

Interpretation

Influence of assumptions: Assumptions about the type of disturbance regime (dispersed vs. aggregated disturbances) result in opposite trends in disturbance return intervals over time. Scenarios representing small disturbances scattered evenly through time (top panels) indicate a continuous increase in mean disturbance intervals up until the last 40 years. Scenarios representing large, episodic disturbances (bottom panels) indicate that disturbance intervals have decreased more or less continuously throughout the analysis period. Further research should try to acquire data about the predominant type of disturbance regime.

Comparison of modern period to pre-settlement period (PSP): All scenarios agree that harvesting in the last 40 years has decreased the mean disturbance interval. If logging has targeted old stands first (right panels), disturbance intervals for the last 20 years are shorter than estimates for the PSP.

Comparison to other BEC variants: The only BEC variant with broadly similar trends of variability in disturbance intervals over time is the ICHvk1.

Other observations: In scenarios representing large, episodic disturbances (bottom panels), uncertainty increases with temporal distance from the present.

Summary Sheets for ICHvk1

The very wet cool variant of the Interior Cedar–Hemlock zone (ICHvk1) occupies ~19 347 ha of the mid-elevations in the Arrow Forest District. It occurs above the ICHwk1 and below the ESSFwc2. Mature forests in this variant consist mostly of Cw and Hw, and Sxw occurs as a seral species or minor component. The *Biodiversity Guidebook* places the ICHvk1 in NDT1, with rare stand-initiating events at mean intervals of 250 years.

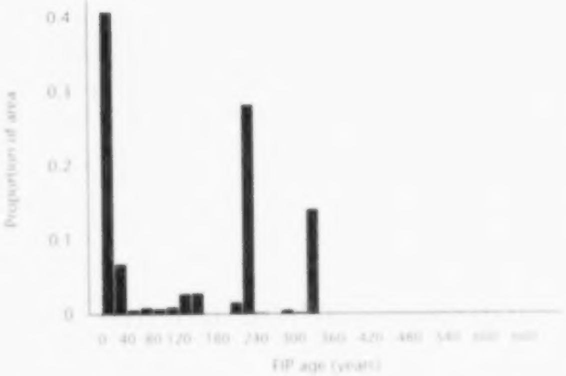


FIGURE 20 *Age distribution for the ICHvk1*

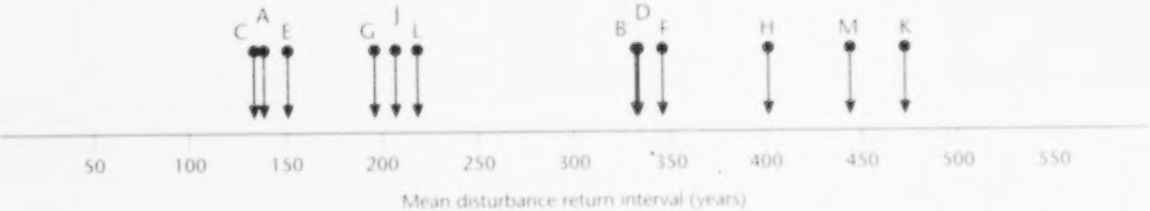


FIGURE 21 *Mean disturbance return intervals (MRIS) for the pre-settlement period (1700–1860).*

Key for Scenarios

A Dispersed disturbances, dispersed FIP error model, even logging hazard

B Dispersed disturbances, dispersed FIP error model, exponential logging hazard

C Dispersed disturbances, aggregated FIP error model, even logging hazard

D Dispersed disturbances, aggregated FIP error model, exponential logging hazard

E Episodic disturbances, dispersed FIP error model, even logging hazard

F Episodic disturbances, dispersed FIP error model, exponential logging hazard

G Episodic disturbances, aggregated FIP error model, even logging hazard

H Episodic disturbances, aggregated FIP error model, exponential logging hazard

J Age-dependent disturbances, dispersed FIP error model, even logging hazard

K Age-dependent disturbances, dispersed FIP error model, exponential logging hazard

L Age-dependent disturbances, aggregated FIP error model, even logging hazard

M Age-dependent disturbances, aggregated FIP error model, exponential logging hazard

Interpretation

Most influential assumptions: Assumptions about the age of stands at time of harvesting appear to have the largest influence on MRI estimates. All scenarios based on exponential logging hazard have longer return intervals than those based on even logging hazard.

Clustering of MRI estimates: See above.

Relation to* Biodiversity Guidebook *(BGB) estimates: The BGB estimate of 250 years falls in the "gap" between estimates based on even logging hazard (A, C, E, G, J, L) and those based on exponential hazard (B, D, F, H, K, M).

Similarities with other BEC variants: None in this study area.

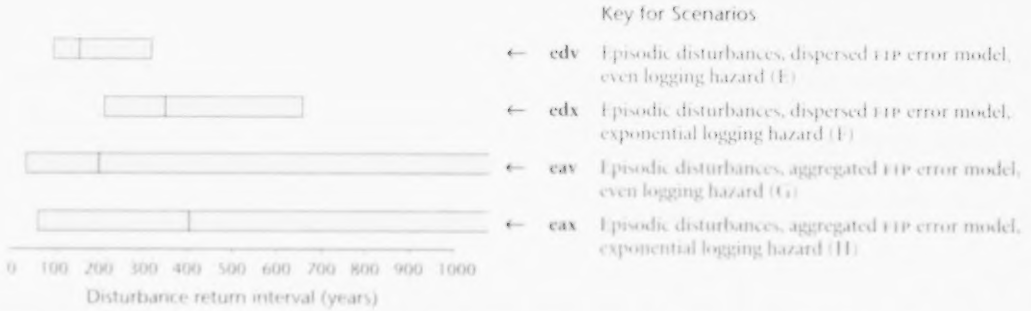


FIGURE 22 *Confidence intervals for estimates of disturbance return intervals of the pre-settlement period (1700–1860).*

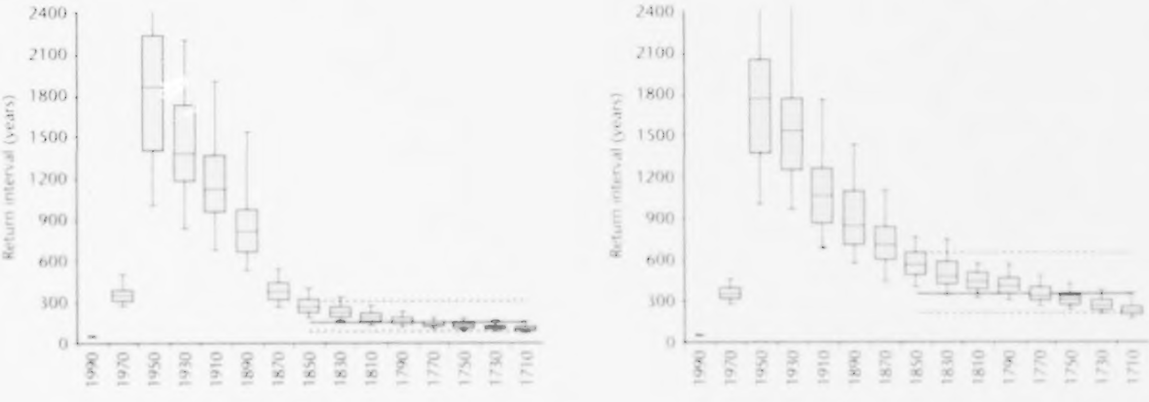
Interpretation

Based on published field studies (see Part 1, this report) and summary information in Braumandl and Curran (editors, 1992), it appears that the historical disturbance regime in the ICHvk1 consisted of infrequent stand-replacing events (with very few fires) and small-scale disturbances in between. Therefore, we consider the *Episodic Scenario* as the best approximation of disturbance dynamics.

Influence of assumptions: The distribution of disturbances over space and time (dispersed vs. aggregated) has some influence on the confidence intervals around MRI estimates but considerable uncertainty is present in all four scenarios.

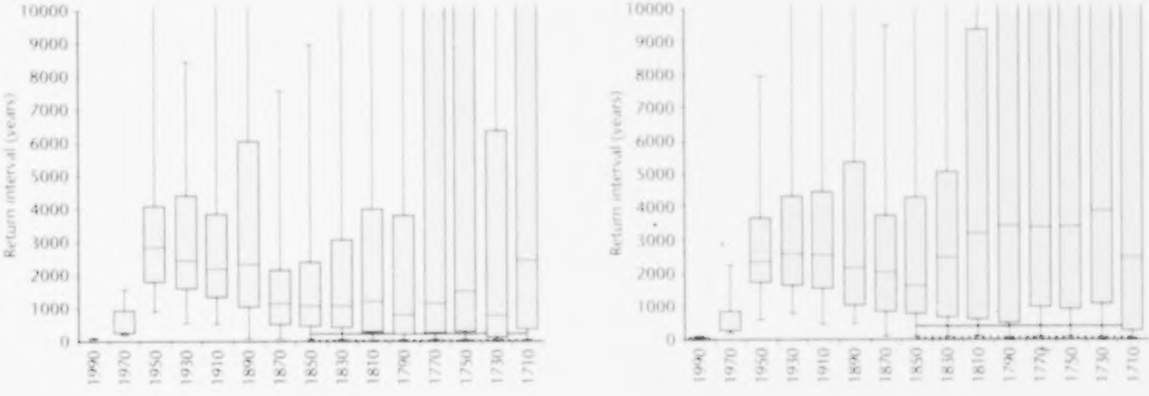
Similarities with other BEC variants: None in this study area.

Other observations: The mean disturbance return intervals of the four scenarios span a wide range (~150–400 yr).



Episodic disturbances, dispersed FIP error model, even logging hazard

Episodic disturbances, dispersed FIP error model, exponential logging hazard



Episodic disturbances, aggregated FIP error model, even logging hazard

Episodic disturbances, aggregated FIP error model, exponential logging hazard

FIGURE 23 *Variability in disturbance return intervals over time, and uncertainty about estimates for each 20-year period between 1700 and 2000.*

Notes: Boxes are bounded by 25% and 75% quartiles and whiskers indicate 5% and 95% quantiles of the data (based on 100 model runs). The solid horizontal line is the mean for the pre-settlement period (1700–1860); dotted horizontal lines indicate the range of variability around this mean (5–95% range). For visual clarity, scales of y-axes often differ, and boxes, whiskers, and lines are sometimes clipped.

Interpretation

Influence of assumptions: Assumptions about the type of disturbance regime (dispersed vs. aggregated disturbances) result in different trends in disturbance return intervals over time. Scenarios representing small disturbances scattered evenly through time (top panels) indicate a continuous increase in mean disturbance intervals up until the last 40 years. Scenarios representing large, episodic disturbances (bottom panels) indicate that disturbance intervals were variable throughout the analysis period. Further research should try to acquire data about the predominant type of disturbance regime in the ICHvk1.

Comparison of modern period to pre-settlement period (PSP): All scenarios agree that harvesting in the last 40 years has decreased the mean disturbance interval, and estimates for the last 20 years are shorter than estimates for the PSP.

Comparison to other BEC variants: The only BEC variant with broadly similar trends of variability in disturbance intervals over time is the ICHvk1.

Other observations: The total area of the ICHvk1 in the Arrow Forest District is very small (<20 000 ha), which likely reduces the reliability of the results obtained in this analysis. As for other variants where results based on the dispersed and aggregated error models are contrasted, scenarios representing small disturbances scattered evenly through time (top panels) show much narrower confidence intervals.

Summary Sheets for ESSFwc1

The Columbia wet cold variant of the Engelmann Spruce–Subalpine Fir zone (ESSFwc1) occupies ~136 839 ha in a narrow mid-elevation band in the Arrow Forest District. It occurs above the ICHmw2 and ICHwk1and below the ESSFwc4. Mature forests in this variant consist mostly of Bl and Se, and Pl occurs as a seral species. The *Biodiversity Guidebook* places the southern areas of the ESSFwc1 in NDT2 with infrequent stand-initiating events at mean intervals of 200 years, and the northern areas in NDT1 with rare stand-initiating events at mean intervals of 350 years.

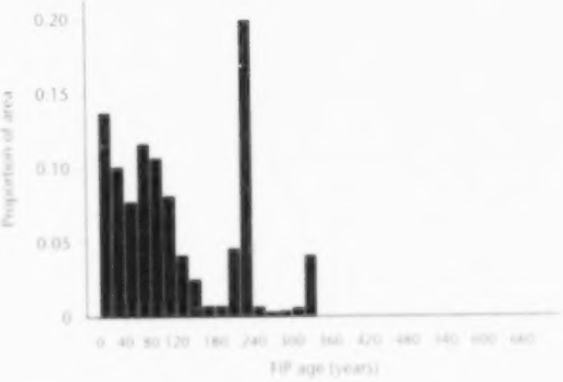


FIGURE 24 *Age distribution for the ESSFwc1.*

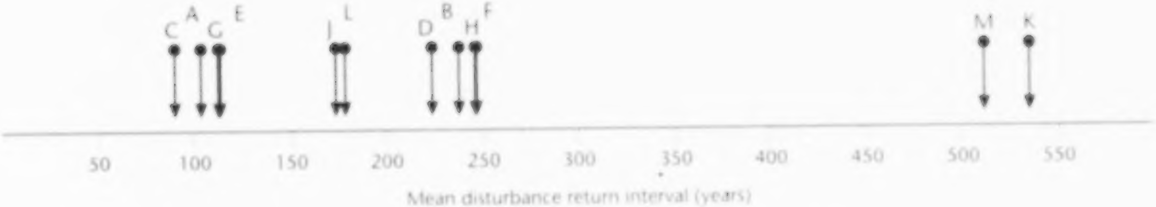


FIGURE 25 *Mean disturbance return intervals (MRIs) for the pre-settlement period (1700–1860).*

Key for Scenarios

- A Dispersed disturbances, dispersed FIP error model, even logging hazard
- B Dispersed disturbances, dispersed FIP error model, exponential logging hazard
- C Dispersed disturbances, aggregated FIP error model, even logging hazard
- D Dispersed disturbances, aggregated FIP error model, exponential logging hazard
- E Episodic disturbances, dispersed FIP error model, even logging hazard
- F Episodic disturbances, dispersed FIP error model, exponential logging hazard
- G Episodic disturbances, aggregated FIP error model, even logging hazard
- H Episodic disturbances, aggregated FIP error model, exponential logging hazard
- J Age-dependent disturbances, dispersed FIP error model, even logging hazard
- K Age-dependent disturbances, dispersed FIP error model, exponential logging hazard
- L Age-dependent disturbances, aggregated FIP error model, even logging hazard
- M Age-dependent disturbances, aggregated FIP error model, exponential logging hazard

Interpretation

Most influential assumptions: If both disturbances and logging impacted mostly older stands (Scenarios K, M), pre-settlement MRI estimates are much longer than for any of the other scenarios. Therefore, targeted field studies or archival work should try to determine whether these assumptions are reasonable.

Clustering of MRI estimates: As in the ICHdw and ICHmw2, assumptions about the age of stands at the time of harvesting separate MRI estimates into three distinct clusters (in addition to the two "outlier" scenarios). Estimates based on even logging hazard are shorter (~110 yr) than those based on exponential logging hazard (~220 yr). Further research should try to acquire data about stand age at logging.

Relation to* Biodiversity Guidebook *(BGB) estimates: The BGB estimate of 200 years for the southern areas of the ESSFwc1 falls in the "gap" between MRI estimates based on even logging hazard (Scenarios A, C, E, G, J, L) and those based on exponential hazard (B, D, F, H). The BGB estimate of 350 years for the northern areas of the ESSFwc1 falls in the "gap" between MRI estimates for the two "outliers" (M, K) and the other scenarios.

Similarities with other BEC variants: The clustering of MRI estimates, though not necessarily the numerical values, are similar to those for the ICHdw and ICHmw2.

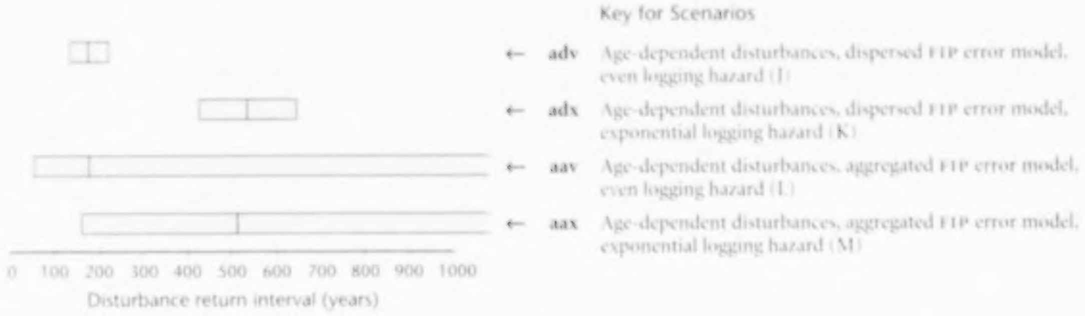


FIGURE 26 *Confidence intervals for estimates of disturbance return intervals of the pre-settlement period (1700–1860).*

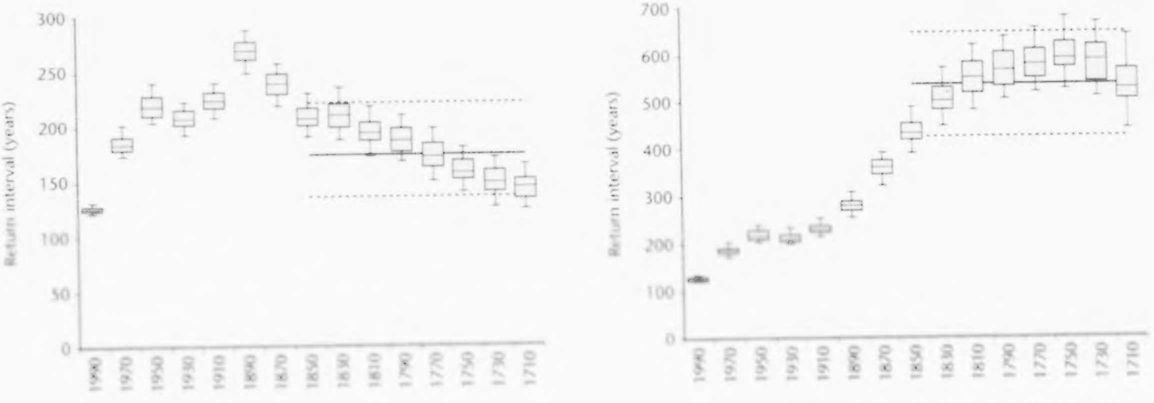
Interpretation

Based on published field studies (see Part 1, this report) and summary information in Braumandl and Curran (editors, 1992), it appears that the historical disturbance regime in the ESSFwc1 consisted of infrequent stand-replacing events, mostly from bark beetle epidemics in the seral Pl stands. Therefore, we consider the *Age-dependent Scenario* as the best approximation of disturbance dynamics.

Influence of assumptions: The distribution of disturbances over space and time (dispersed vs. aggregated) has a large influence on the confidence intervals around MRI estimates. Therefore, further research should try to resolve whether clusters in the FIP age are artifacts of air photo interpretation.

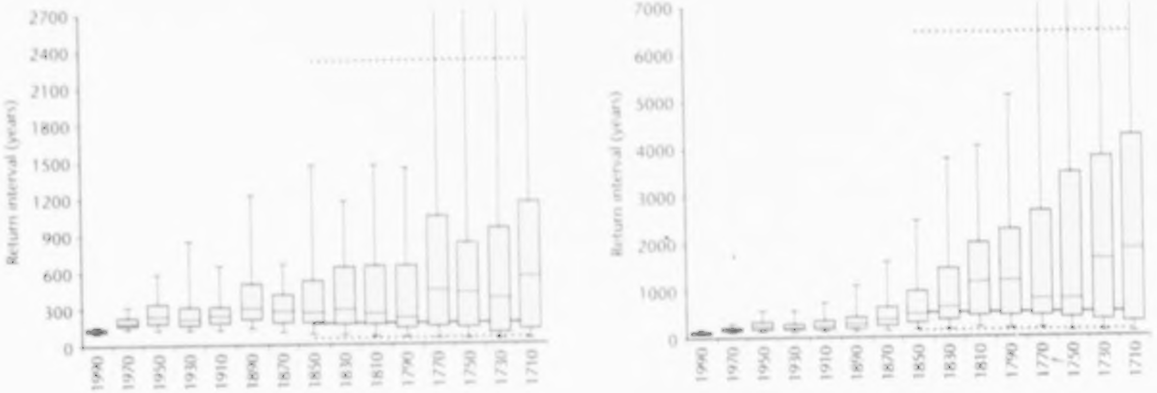
Similarities with other BEC variants: BEC variants with similar issues regarding the width of confidence intervals are the ICHdw, ICHwk1, ESSFwc4, and ESSFwcp4.

Other observations: The mean disturbance return intervals of the four scenarios span a wide range (~170–530 yr).



Age-dependent disturbances, dispersed FIP error model, even logging hazard

Age-dependent disturbances, dispersed FIP error model, exponential logging hazard



Age-dependent disturbances, aggregated FIP error model, even logging hazard

Age-dependent disturbances, aggregated FIP error model, exponential logging hazard

FIGURE 27 *Variability in disturbance return intervals over time, and uncertainty about estimates for each 20-year period between 1700 and 2000.*

Notes: Boxes are bounded by 25% and 75% quartiles and whiskers indicate 5% and 95% quantiles of the data (based on 100 model runs). The solid horizontal line is the mean for the pre-settlement period (1700–1860); dotted horizontal lines indicate the range of variability around this mean (5–95% range). For visual clarity, scales of y-axes often differ, and boxes, whiskers, and lines are sometimes clipped.

Interpretation

Influence of assumptions: Assumptions about the age of stands at time of harvesting (left vs. right panels) result in different trends in disturbance return intervals over time but are more pronounced in the years after 1860. Therefore, further research should try to acquire data about stand age at the time of harvesting.

Comparison of modern period to pre-settlement period (PSP): If all harvestable stands were targeted equally (left panels), modern disturbance intervals are similar to estimates for the PSP. On the other hand, scenarios based on exponential logging hazard (right panels) show a decrease in disturbance intervals since 1860 and modern disturbance intervals are outside the range of PSP variability.

Comparison to other BEC variants: The only other BEC variant with broadly similar trends of variability in disturbance intervals over time is the ICHmw2. This might be an artifact of choosing the same basic disturbance scenario, but could also be caused by the closeness of the two variants.

Other observations: Uncertainty generally increases with temporal distance from the present but more so in the scenarios representing large, episodic disturbances (bottom panels). In addition, these scenarios offer less confidence in disturbance return intervals than scenarios with small disturbances scattered more evenly through time.

Summary Sheets for ESSFwc4

The Selkirk wet cold variant of the Engelmann Spruce–Subalpine Fir zone (ESSFwc4) occupies ~337 417 ha at mid to high elevations in the Arrow Forest District. It occurs above the ICHwk1 and ESSFwc1 and below the ESSFwcp4. Mature forests in this variant consist mostly of Bl and Se, and Pl occurs as a minor component. The *Biodiversity Guidebook* places the southern areas of the ESSFwc4 in NDT2 with infrequent stand-initiating events at mean intervals of 200 years, and the northern areas in NDT1 with rare stand-initiating events at mean intervals of 350 years.

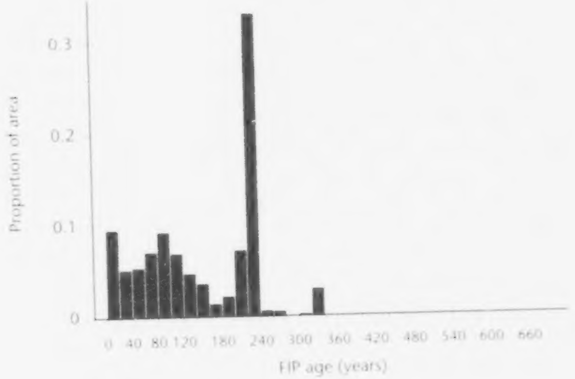


FIGURE 28 *Age distribution for the ESSFwc4.*

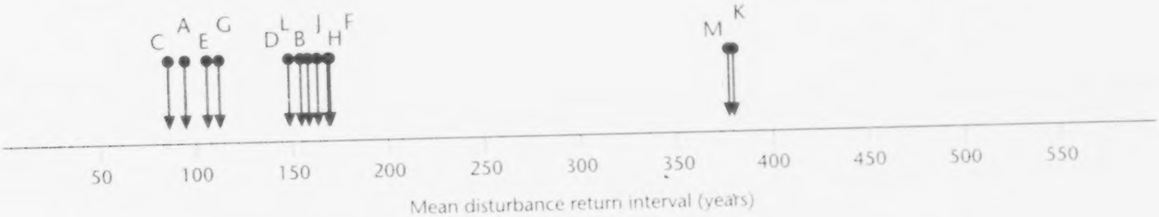


FIGURE 29 *Mean disturbance return intervals (MRIs) for the pre-settlement period (1700–1860).*

Key for Scenarios

A Dispersed disturbances, dispersed FIP error model, even logging hazard
B Dispersed disturbances, dispersed FIP error model, exponential logging hazard
C Dispersed disturbances, aggregated FIP error model, even logging hazard
D Dispersed disturbances, aggregated FIP error model, exponential logging hazard
E Episodic disturbances, dispersed FIP error model, even logging hazard
F Episodic disturbances, dispersed FIP error model, exponential logging hazard
G Episodic disturbances, aggregated FIP error model, even logging hazard
H Episodic disturbances, aggregated FIP error model, exponential logging hazard
J Age-dependent disturbances, dispersed FIP error model, even logging hazard
K Age-dependent disturbances, dispersed FIP error model, exponential logging hazard
L Age-dependent disturbances, aggregated FIP error model, even logging hazard
M Age-dependent disturbances, aggregated FIP error model, exponential logging hazard

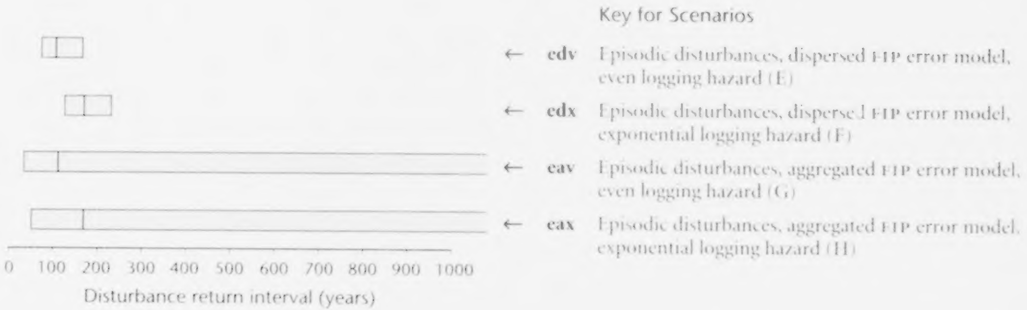
Interpretation

Most influential assumptions: If both disturbances and logging impacted mostly older stands (Scenarios K, M), pre-settlement MRI estimates are much longer than for any of the other scenarios. Therefore, targeted field studies or archival work should try to determine whether these assumptions are reasonable.

Clustering of MRI estimates: Assumptions about the age of stands at the time of harvesting separate MRI estimates into two distinct clusters (in addition to the two "outlier" scenarios). Estimates based on even logging hazard are shorter (~100 yr) than those based on exponential logging hazard (~170 yr). Further research should try to acquire data about stand age at logging.

Relation to* Biodiversity Guidebook *(BGB) estimates: The BGB estimate of 200 years for the southern areas of the ESSFwc4 falls in the "gap" between MRI estimates for the two "outliers" (M, K) and the other scenarios. The BGB estimate of 350 years for the northern areas of the ESSFwc4 is similar to the MRI estimate of the two "outliers" (M, K). All MRI estimates, except for Scenarios K and M, appear low for high-elevation forests, relative to published research.

Similarities with other BEC variants: The clustering of MRI estimates, though not necessarily the numerical values, are similar to those for the ICHwk1 and ESSFwcp4.



Key for Scenarios

← **edv**	Episodic disturbances, dispersed FIP error model, even logging hazard (E)
← **edx**	Episodic disturbances, dispersed FIP error model, exponential logging hazard (F)
← **eav**	Episodic disturbances, aggregated FIP error model, even logging hazard (G)
← **eax**	Episodic disturbances, aggregated FIP error model, exponential logging hazard (H)

FIGURE 30 *Confidence intervals for estimates of disturbance return intervals of the pre-settlement period (1700–1860).*

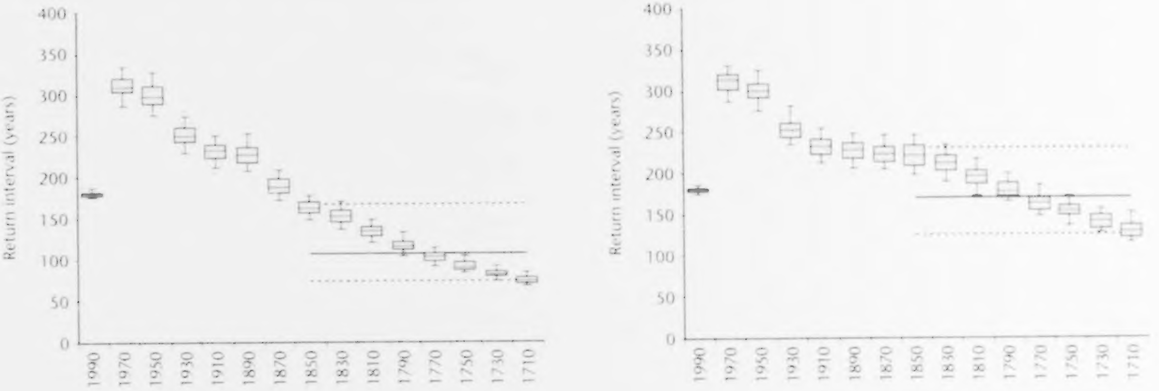
Interpretation

Based on published field studies (see Part 1, this report) and summary information in Braumandl and Curran (editors, 1992), it appears that the historical disturbance regime in the ESSFwc4 consisted of infrequent stand-replacing events (with very few fires) and small-scale disturbances in between. Therefore, we consider the *Episodic Scenario* as the best approximation of disturbance dynamics.

Influence of assumptions: The distribution of disturbances over space and time (dispersed vs. aggregated) largely influences the confidence intervals around MRI estimates. Therefore, further research should try to resolve whether clusters in the FIP age are artifacts of air photo interpretation.

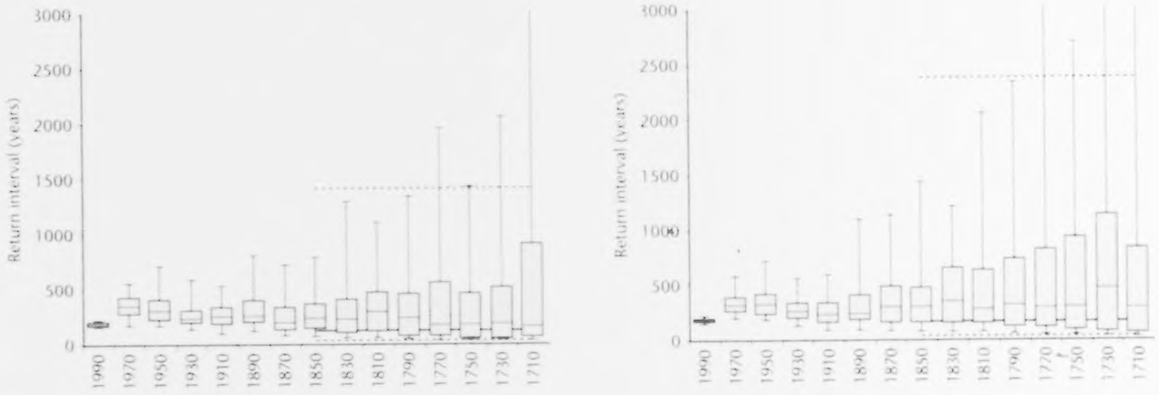
Similarities with other BEC variants: BEC variants with similar issues regarding the width of confidence intervals are the ICHdw, ICHwk1, ESSFwc1, and ESSFwcp4.

Other observations: The mean disturbance return intervals of the four scenarios span a narrow range (~110–170 yr). The four MRI estimates are lower than the BGB estimate of 200 or 350 years. However, uncertainty under the aggregated FIP error model is substantial, and BGB estimates are well within the confidence intervals for this error model.



Episodic disturbances, dispersed FIP error model, even logging hazard

Episodic disturbances, dispersed FIP error model, exponential logging hazard



Episodic disturbances, aggregated FIP error model, even logging hazard

Episodic disturbances, aggregated FIP error model, exponential logging hazard

FIGURE 31 *Variability in disturbance return intervals over time, and uncertainty about estimates for each 20-year period between 1700 and 2000.*

Notes: Boxes are bounded by 25% and 75% quartiles and whiskers indicate 5% and 95% quantiles of the data (based on 100 model runs). The solid horizontal line is the mean for the pre-settlement period (1700–1860); dotted horizontal lines indicate the range of variability around this mean (5–95% range). For visual clarity, scales of y-axes often differ, and boxes, whiskers, and lines are sometimes clipped.

Interpretation

Influence of assumptions: Assumptions about the type of disturbance regime (dispersed vs. aggregated disturbances) result in different trends in disturbance return intervals over time. Scenarios representing small disturbances scattered evenly through time (top panels) indicate a continuous increase in mean disturbance intervals up until the last 20 years. Scenarios representing large, episodic disturbances (bottom panels) indicate that disturbance intervals increased less strongly and remained more variable throughout the analysis period. Further research should try to acquire data about the predominant type of disturbance regime in the ESSFwc4.

Comparison of modern period to pre-settlement period (PSP): All scenarios agree that harvesting in the last 20 years has decreased the mean disturbance interval. However, only for the scenario assuming even logging hazard and small disturbances scattered evenly through time (top left panel) are disturbance intervals for the last 20 years shorter than estimates for the PSP.

Comparison to other* BEC *variants: The only other BEC variant with broadly similar trends of variability in disturbance intervals over time is the ESSFwc4.

Other observations: In scenarios representing large, episodic disturbances (bottom panels), uncertainty increases with temporal distance from the present.

Summary Sheets for ESSFwcp4

The Selkirk wet cold parkland variant of the Engelmann Spruce–Subalpine Fir zone (ESSFwcp4) occupies ~98 989 ha at high elevations in the Arrow Forest District. It occurs above the ESSFwc1 and ESSFwc4 and forms the highest forested zone. Mature forests in this variant consist mostly of Bl, with Se occurring as a minor component. The *Biodiversity Guidebook* places the ESSFwcp4 in NDT5, with no estimates for the type or frequency of natural disturbances.

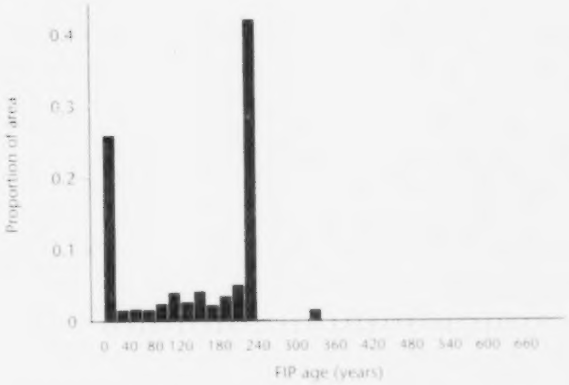


FIGURE 32 *Age distribution for the ESSFwcp4.*

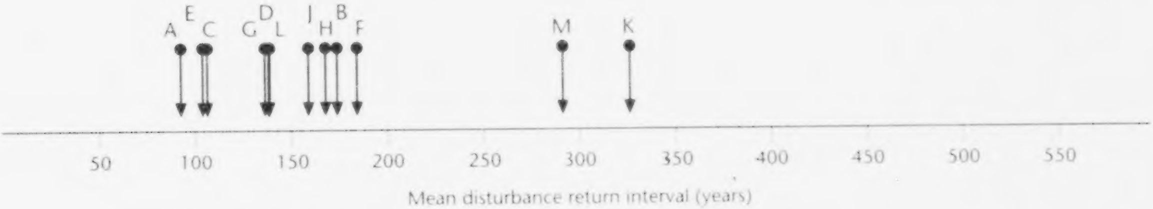


FIGURE 33 *Mean disturbance return intervals (MRIs) for the pre-settlement period (1700–1860).*

Key for Scenarios

A Dispersed disturbances, dispersed FIP error model, even logging hazard

B Dispersed disturbances, dispersed FIP error model, exponential logging hazard

C Dispersed disturbances, aggregated FIP error model, even logging hazard

D Dispersed disturbances, aggregated FIP error model, exponential logging hazard

E Episodic disturbances, dispersed FIP error model, even logging hazard

F Episodic disturbances, dispersed FIP error model, exponential logging hazard

G Episodic disturbances, aggregated FIP error model, even logging hazard

H Episodic disturbances, aggregated FIP error model, exponential logging hazard

J Age-dependent disturbances, dispersed FIP error model, even logging hazard

K Age-dependent disturbances, dispersed FIP error model, exponential logging hazard

L Age-dependent disturbances, aggregated FIP error model, even logging hazard

M Age-dependent disturbances, aggregated FIP error model, exponential logging hazard

Interpretation

Most influential assumptions: If both disturbances and logging impacted mostly older stands (Scenarios K, M), pre-settlement MRI estimates are much longer than for any of the other scenarios. Therefore, targeted field studies or archival work should try to determine whether these assumptions are reasonable.

Clustering of MRI estimates: Different types of assumptions do not result in obvious clusters (other than the two "outlier" scenarios). However, estimates based on even logging hazard are generally shorter (~120 yr) than those based on exponential logging hazard (~170 yr). Further research should try to acquire data about stand age at logging.

Relation to* Biodiversity Guidebook *(BGB) estimates: The BGB does not provide an estimate. However, all MRI estimates except for scenarios K and M appear low for high-elevation forests, relative to published research.

Similarities with other BEC variants: The clustering of MRI estimates, though not necessarily the numerical values, are similar to those for the ICHwk1 and ESSFwc4.

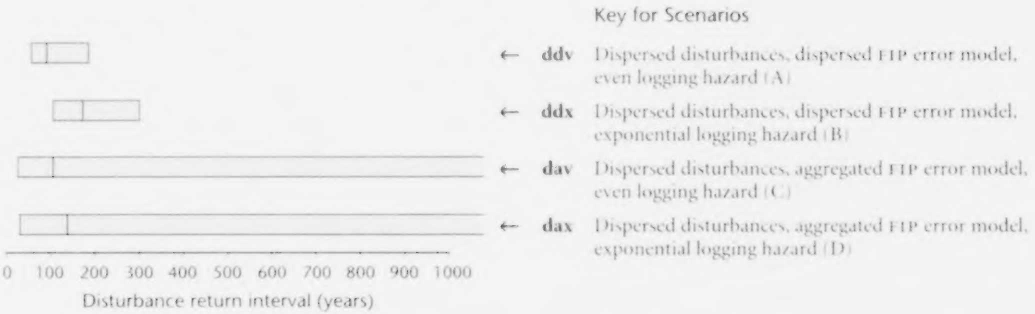


FIGURE 34 *Confidence intervals for estimates of disturbance return intervals of the pre-settlement period (1700–1860).*

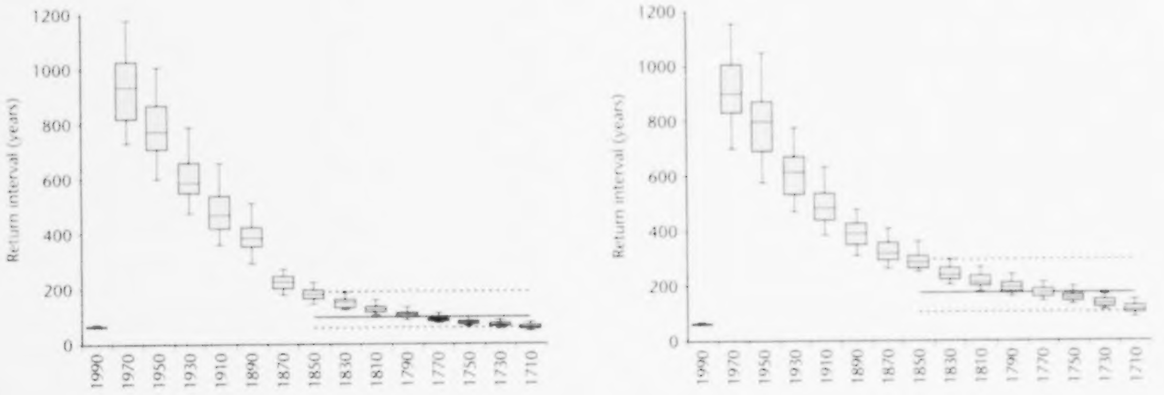
Interpretation

Based on published field studies (see Part 1, this report) and summary information in Braumandl and Curran (editors, 1992), it appears that the historical disturbance regime in the ESSFwcp4 consisted mostly of local events (mostly windthrow, avalanches, and insect damage) with a wide range of severities. Therefore, we consider the *Dispersed Scenario* as the best approximation of disturbance dynamics.

Influence of assumptions: The distribution of disturbances over space and time (dispersed vs. aggregated) largely influences the confidence intervals around MRI estimates. Therefore, further research should try to resolve whether clusters in the FIP age are artifacts of air photo interpretation.

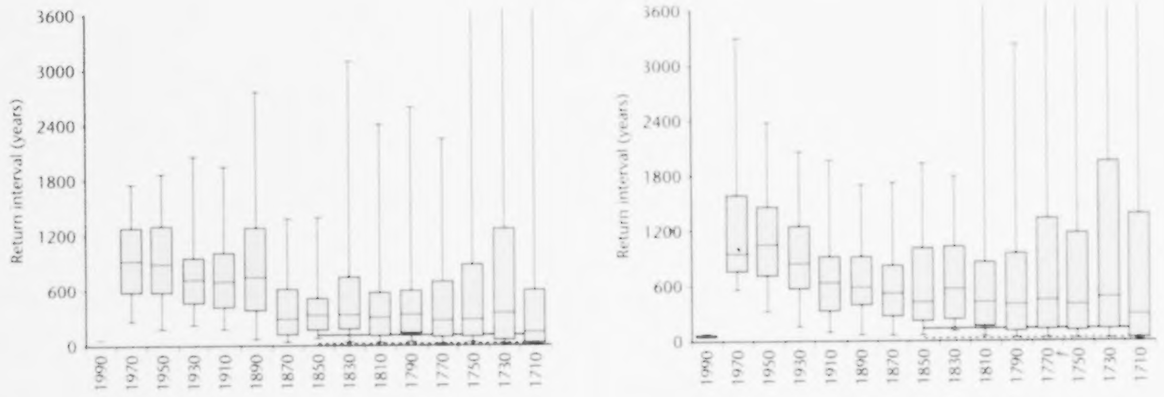
Similarities with other BEC variants: BEC variants with similar issues regarding the width of confidence intervals are the ICHdw, ICHwk1, ESSFwc1, and ESSFwc4.

Other observations: The mean disturbance return intervals of the four scenarios span a relatively narrow range (~90–170 yr).



Dispersed disturbances, dispersed FIP error model, even logging hazard

Dispersed disturbances, dispersed FIP error model, exponential logging hazard



Dispersed disturbances, aggregated FIP error model, even logging hazard

Dispersed disturbances, aggregated FIP error model, exponential logging hazard

FIGURE 35 *Variability in disturbance return intervals over time, and uncertainty about estimates for each 20-year period between 1700 and 2000.*

Notes: Boxes are bounded by 25% and 75% quartiles and whiskers indicate 5% and 95% quantiles of the data (based on 100 model runs). The solid horizontal line is the mean for the pre-settlement period (1700–1860); dotted horizontal lines indicate the range of variability around this mean (5–95% range). For visual clarity, scales of y-axes often differ, and boxes, whiskers, and lines are sometimes clipped.

Interpretation

Influence of assumptions: Assumptions about the type of disturbance regime (dispersed vs. aggregated disturbances) result in different trends in disturbance return intervals over time. Scenarios representing small disturbances scattered evenly through time (top panels) indicate a continuous increase in mean disturbance intervals up until the last 20 years. Scenarios representing large, episodic disturbances (bottom panels) indicate that disturbance intervals increased less strongly and remained more variable throughout the analysis period. Further research should try to acquire data about the predominant type of disturbance regime in the ESSFwc4.

Comparison of modern period to pre-settlement period (PSP): All scenarios agree that harvesting in the last 20 years has decreased the mean disturbance interval. Disturbance intervals for the last 20 years are shorter than estimates for the PSP when we assumed an exponential logging hazard and even distribution of small disturbances through time (top right panel).

Comparison to other BEC variants: The only other BEC variant with broadly similar trends of variability in disturbance intervals over time is the ESSFwc4.

Other observations: In scenarios representing large, episodic disturbances (bottom panels), uncertainty increases slightly with temporal distance from the present.

It is difficult to determine whether the extremely short disturbance intervals for the 1980–2000 period are due to logging or a problem with the FIP data. A large proportion of the area in the youngest age class comes from polygons designated as productive forest with PROJ_AGE set to zero. Normally, this should indicate very recent cutblocks, but it seems highly unlikely that this much harvesting would have occurred in subalpine forest within the most recent years.

3.7 Discussion

The main objective of this part of our report is to demonstrate an application of the process—as outlined in Part 2—of selecting and using one of the quantitative methods. Primarily, we wanted to show the potential of using FIP data for disturbance analysis, with careful attention to the various sources of uncertainty researchers are likely to encounter with this particular source of data, including uncertainty about data accuracy, historical disturbance dynamics, and historical harvesting activities. Consequently, the following discussion focuses on understanding the implications of various sources of uncertainty for our ability to reconstruct historical disturbance rates. We will also briefly address the emerging issues around guiding forest management based on uncertain and highly variable past conditions.

Uncertainty in the Source Data—FIP Accuracy

Although many studies that use forest inventory data for landscape analysis address potential errors in these data, authors are typically primarily concerned about systematic bias (Hawkes et al. 1997; Pollack et al. 1997; Andison 1999). However, a constant additive bias, such as the one introduced by regeneration delay, has only a minor effect on estimates of long-term average disturbance rates, because these estimates are based on relative proportions of forest in different age classes.[37] Additive error terms mostly cancel out in these calculations (see also Reed 1994). Consequently, systematic bias is a significant concern for the type of age structure analysis presented here only if bias increases with age.

The random component of scatter in FIP age around true age has received less attention in other studies. In our analysis, it had substantial influence on the results. Uncertainty in FIP age obscures temporal coincidence between patterns in disturbance occurrence, climatic conditions, and/or human management activities. Thus, defining periods with distinct hypothesized dynamics, such as an "early settlement period," and comparing disturbance rates during that period to those of other periods can be problematic. This is because a significant proportion of the stands initiated during that period may have been misdated and assigned to an earlier or later time period instead. The wide confidence intervals for pre-settlement rates obtained under the aggregated FIP error model are largely a consequence of this problem. They are caused by model runs where large clusters of "midpointed" stands[38] are reassigned to age groups in the pre-settlement period or the oldest collector class, resulting in very low disturbance rates for the pre-settlement period.

Uncertainty in the FIP data also obscures the degree of "roughness," or fluctuations, inherent in the true age-class distribution. An accurate assessment of this roughness is critical because it directly translates into the size of period-to-period variability in disturbance rates. Unfortunately, reconstructing the fluctuations of the true age distribution is difficult. One reason is that it is unknown whether the area in the FIP clusters created by midpointing is distributed evenly across the entire range of the age class or is instead primarily contained in a few large even-aged cohorts. Another reason is that if the true age distribution had large "spikes"—corresponding to large disturbance events—these would likely be dampened in the FIP data; random dating mistakes by the interpreters would tend to remove polygons disproportionately from the year with the big episode and assign them to surrounding years with lower disturbance occurrence.

A similar "smoothing" of the age distribution occurs when the dispersed model of FIP error is applied to it. This effect tends to create similar age distributions for individual simulation runs, resulting in relatively narrow confidence intervals. Therefore, the results for the dispersed model of FIP error suggest a relatively high degree of confidence, which in some cases may be deceptive. The aggregated model does not have this smoothing effect and consequently results in rougher age distributions. Unfortunately, neither model of FIP error can be expected to accurately reconstruct the roughness in the true age distribution. However, we can be relatively confident that the dispersed model of FIP error provides a lower bound on historical variability in disturbance rates and likely underestimates this variability.

In summary, uncertainty in FIP age substantially affects our ability to accurately reconstruct disturbance history, even though one might intuitively expect that random error should be a less serious problem than systematic bias.

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[37] As long as all age classes are assumed to be equally susceptible to disturbance.

[38] We use the term "midpointed" to indicate the practice of using age-class midpoints as a surrogate for age in the conversion from age-class to age-based interpretation standards. See also the section on interpretation of FIP age clusters in the section on modelling FIP error.

Uncertainty about Historical Disturbance Dynamics

A fundamental source of uncertainty about historical disturbance dynamics in the Arrow Forest District concerns the influence of early settlement activities, as well as the impact of modern forest management, including fire suppression. We thus assumed that a stationary disturbance regime is inappropriate, at least for the period spanning the last century. Although the Rollback Method (as well as Method 2-A) addresses non-stationary disturbance dynamics, the lack of knowledge about historical forest management and early-settlement activities still affects our ability to draw accurate inferences about natural disturbance dynamics. In general, evidence of past events becomes less certain as we reach back in time and the period of record is limited to the average lifespan of the dominant tree species.

The ideal outcome of an analysis of disturbance frequency would be to infer the properties of natural disturbance dynamics entirely from the available data. In practice, a certain degree of *a priori* understanding of natural dynamics is required to develop or choose the appropriate sampling design and method(s) of analysis. Our application example should illustrate that the information contained in the FIP age structure is limited and that information on historical disturbance rates can be extracted from it only by making several specific *a priori* assumptions about historical disturbance dynamics. Put another way, the results obtained are sensitive to the assumptions made in the analysis, and these assumptions therefore need to be carefully formulated. Note that this observation generally holds for analyses based on FIP age, irrespective of the method or methods used. The Rollback Method appears to result in greater uncertainty than alternative procedures, such as Method 1-A or 1-B (see Part 2), because it makes its assumptions more explicitly and therefore allowed us to explore their impact on the results.

Some of the uncertainty surrounding historical dynamics, in particular the question about to what degree historical disturbance dynamics were driven by large episodic events, could be resolved if the input data were more accurate. However, other questions, such as age-dependent susceptibility to disturbance, can simply not be addressed from time-since-disturbance data without making other limiting *a priori* assumptions.

To increase the confidence in results, studies such as this one are probably best carried out as an iterative process. A first round of analysis would pinpoint sources of uncertainty that have large leverage on results. These can then be addressed through targeted field studies or archival work. Once these have been completed, the analysis would be repeated with a reduced or refined set of assumptions and scenarios.

In this demonstration study, we were primarily interested in exploring the effects of different sets of assumptions on the outcome of the analysis. Because we wanted to determine the robustness of results and general conclusions, we selected extreme "cornerstone scenarios" meant to delimit the full range of potential disturbance dynamics one might reasonably expect in the area. It is important to realize in this context that the assumptions commonly made in similar analyses of disturbance frequency likely represent only one end of the spectrum and that these analyses may consequently be biased towards finding short return intervals. In particular, assuming no age dependence in susceptibility to disturbance is a "lower-bound" assumption because it will lead to shorter return intervals than assuming some form of increasing susceptibility with age.

Removing harvested areas from analysis (e.g., Andison 2000) also results in a bias towards shorter return intervals (see Pollack et al. 1997). One method commonly used to address the problem of unknown pre-harvest age is to fill in harvested areas by extrapolation from adjacent polygons (e.g., Hawkes et al. 1997; Morgan 1999, 2001). If the distribution of seral stages is reasonably homogeneous across the landscape, this should result in harvested polygons being proportionally assigned to age classes beyond harvesting age and thus produce results similar to our even-logging-hazard scenarios. Again, this is a "lower-bound" assumption, because it seems unlikely that harvesting would have predominantly targeted younger age classes. Finally, we have already discussed how the dispersed model of FIP error represents a "lower-bound" assumption for overall variability and uncertainty found in the results. The age-dependent scenarios, exponential pre-harvesting age scenarios, and the aggregated model of FIP error were selected to counterbalance these "lower-bound" assumptions with "upper-bound" assumptions.

Lastly, this study emphasizes the need to maintain records of harvesting and other management activities, as well as ongoing natural disturbance activity. We expect that this will become a topic of increasing concern as more and more of the landscape is harvested and older versions of forest inventory data are lost or made less accessible by changes in archiving technology. If the history of anthropogenic and natural changes to the forest is not recorded and maintained, the value of forest inventory data for research on historical landscape dynamics will be increasingly limited.

Presentation and Interpretation of Complex and Uncertain Results

The complex interactions between temporal variation, stochastic modelling, and data sources of limited accuracy present formidable challenges for meaningful presentation and interpretation of the results. In the first part of this section, we tried to outline a structured and transparent approach to this task. Likewise, the summary sheets contain our ideas as to how such complex information can be presented and summarized consistently. Of course, other kinds of graphs, tables, and written summaries could serve this purpose equally well.

Using summary sheets highlights those aspects of the output data that any format of presentation should include. To summarize, these are:

- Comparing (relatively) all scenarios, for example by comparing estimates for pre-settlement period intervals.
- Providing a clear rationale for focusing on specific scenarios for in-depth analyses based on published data or expert opinion.
- Using confidence intervals to visualize the effects of uncertainty about the quality of the input data.
- Showing how disturbance rates have changed over time.
- Highlighting the effects of increasing uncertainty when moving back in time.
- In presenting results, carefully distinguishing between temporal variability in disturbance rates and uncertainty about data quality. This distinction should be clear both in the representation chosen in the graphs and in the verbal discussion of results.
- Choosing and representing a reference period, if desired, in a transparent fashion. For example, our graphs show both a representation of the "pre-settlement regime" and the variability in reconstructed historical disturbance dynamics within that time period.

In addition to presenting results by BEC variant, a comparison among variants might help to detect and assess differences and similarities in disturbance rates and trends. For example, a graph of relative disturbance rates for a given time period and scenario(s), standardized with the rate for the entire study area, could help to pinpoint ecological as well as technical aspects of the results. However, we caution anyone undertaking these kinds of comparisons to always consider the context of the underlying methods and data to avoid simplistic or nonsensical conclusions.

Historical Disturbance Dynamics and Forest Management

The general trends in disturbance rates, as estimated for the Arrow Forest District, are in accordance with patterns found in nearby study areas (e.g., McCune 1983; Van Wagner 1995; Andison 2000). For many biogeoclimatic variants, we found a decrease in disturbance rates during the later parts of the 20th century, at least up until industrial logging began. However, the size of decrease is well within the range of historical fluctuations in disturbance rates for most scenarios and our results provide no obvious support for the hypothesis that fire suppression has been effective in the Arrow Forest District. Consequently, it seems advisable to consider the possibility of recurrence of larger disturbance episodes, which may prove to be difficult to suppress (e.g., Johnson and Wowchuk 1993), and to allow for losses to natural disturbance when determining harvest rates and setting landscape objectives for late-seral forest and old forest connectivity.

Incorporating information about historical variability in landscape dynamics into forest planning and management is a quickly expanding field of research and discussion and beyond the scope of this project. For example, recent editions of the peer-reviewed journals *Ecological Applications* and *Forest Ecology and Management* contain special sections focusing on historical variability (Parsons et al. 1999) and natural disturbances as a guide to forest management (Mitchell et al. 2002), respectively. Additional discussions, reviews, and application examples are presented by, for example, Swanson et al. (1997), Lertzman and Fall (1998), Wong and Iverson (2001), and Dorner (2002).

One of the primary conclusions of this analysis is that historical disturbance rates were highly variable. Although we do not show the corresponding results for seral stage proportions here, clearly, for example, relative historical proportions of mature and late-seral forest were also highly variable throughout history.[39] Incorporating this "constancy of change" into forest management means moving away from steady-state targets such as the ones used in the *Biodiversity Guidebook* and embracing the concept of the range of historical variability (see Swanson et al. 1994) as a management guideline that more closely reflects ecological reality.

In the present context, we emphasize that forest ecosystems have historically experienced a wide range of dynamics. While species dependent on old forest have clearly persisted through periods with extensive disturbance episodes (where old forest was scarce), this does not imply that static management at the lower end of the reconstructed HRV—that is, the minimum amount of old forest during the period of reference—will ensure the persistence of these species in the future. Spatial and temporal variability are important factors facilitating persistence or loss of species throughout landscapes (e.g., Lertzman et al. 1998; Wimberly et al. 2000). Thus, management "somewhere within HRV" cannot be considered an ecologically adequate objective unless efforts are made to manage for the full range of historical dynamics.

In Part 4 of our report we present several general recommendations regarding the implementation of disturbance research, such as the data resulting from the Arrow Forest District analysis, into forest planning and management. As a "bridge" to these recommendations, we conclude this third part of the report with a cautionary note.

Our application example focuses exclusively on the frequency of natural disturbances. The results provide important historical context for short-term variability and long-term trends of disturbance regimes. However, timber harvesting differs from natural disturbances in several important aspects and the effects of natural and anthropogenic disturbances are cumulative. For instance, harvesting does not target all age groups equally. Thus, even if forest management perfectly emulated historical disturbance rates, the resulting landscape would likely contain much less forest in the older age classes than there was historically (Bergeron et al. 1999). Considering rates of disturbances in isolation cannot ensure that forest ecosystems will be maintained within their range of historical conditions. To accomplish this goal, forest management needs to be equally concerned with seral stage distributions and other spatio-temporal aspects of landscape pattern (Eng 1998).

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[39] Results for proportion of old forest in the landscape can be found in the EXCEL spreadsheets available from B. Dorner.

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4 RECOMMENDATIONS FOR FUTURE WORK

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4.1 Introduction

Natural disturbances are an integral component of the processes shaping and maintaining forested landscapes and continue to directly influence all aspects of forest management. In the first part of this report, we presented an overview of the state of knowledge about the historical variability of natural disturbances in British Columbia. In Part 2, we provided a catalogue of methods available for estimating their frequency. In Part 3, we presented an example for reconstructing stand-replacing disturbances based on FIP data. In all three parts, we have identified and discussed important challenges to quantifying and interpreting the historical variability of natural disturbances in British Columbia. In this fourth and final part, we present general lessons and recommendations for determining and using best possible estimates of disturbance intervals and other disturbance attributes. First, we offer recommendations regarding research, data collection, and data maintenance, as well as quantitative methods and tools, and end with recommendations for developing methods for incorporating disturbance research into forest planning and management.

4.2 Recommendations Regarding Research

In Part 1 of this report, we identified gaps in research about natural disturbances in British Columbia. We recommend that these gaps be filled to reduce the uncertainty in current knowledge about disturbance dynamics. Because the gaps are many and resources are limited, we suggest that the gaps be ranked to prioritize research efforts.

Gaps in geographical coverage of research.

- Two BEC zones, AT and CDF, with no B.C.–specific research on disturbance intervals.
- Forty BEC subzones with no B.C.–specific research on disturbance dynamics.
- Many subzones with only one study on disturbance dynamics in one variant.

Recommendations:

1. *Conduct surveys or regional workshops with expert ecologists to prioritize which biogeoclimatic zones, subzones, or variants should be researched. Priorities should be based on the extent of the ecosystem in British Columbia, the variability within that ecosystem, the "threat" to historical evidence in that ecosystem, the degree of hypothesized departure from the range of natural variability, socio-economic concerns and values, and the temporal and spatial depth and quality of existing research.*
2. *Conduct surveys or regional workshops to develop a western North American list of "equivalent ecosystems" to add to the Shining Mountain Project, which extended biogeoclimatic mapping to states bordering British Columbia (A. MacKinnon, pers. comm., 2003). Substantial research on natural disturbances conducted in other Canadian provinces or the United States has the potential to provide proximal data for British Columbia subzones/variants currently without research—and vice versa—or to allow for comparison of results and methods. Unfortunately, ecosystem classifications in most other jurisdictions, unlike biogeoclimatic ecological classification, do not incorporate regional climate. Given that climate influences disturbance patterns (DeLong 1998; Swetnam and Betancourt 1998), these classifications may not adequately describe similar regimes of natural disturbances.*

Gaps in research on disturbance agents other than fire and interactions between disturbances, human activities, and future climate change.

- Most research has focused on fire. Although some research has focused on historical insect dynamics, this is limited in British Columbia to specific species and locations. The historic variability of other disturbance agents, such as windthrow, diseases, and animal damage, is very poorly described in British Columbia.
- Interactions between disturbances, human activities, and future climate change are poorly understood both in and outside British Columbia. Similarly, we still lack basic knowledge about how and to what degree the effects of natural disturbance differ from those of anthropogenic disturbance (e.g., Palik et al. 2002; Seymour et al. 2002; Dorner and Lertzman, in prep.).

Recommendations:

3. *Conduct surveys or workshops with expert ecologists to prioritize which disturbance agents within which biogeoclimatic zones/subzones or other unit of classification should receive research focus. Prioritization should be based on the relative influence of each disturbance agent in a subzone or other unit, the spatial and temporal depth and quality of existing research, and socio-economic concerns and values. This research will help to improve operational adjustment factors (OAFs).*
4. *Because of the challenges in gathering empirical data that directly quantify interactions, simulation modelling is a useful tool for assessing strengths of and feedback loops among interactions (e.g., Fall 1999; Sachs 1999; Morgan 2001). In these models, agent-specific data can be integrated with models of timber harvesting and climate change to assess long-term dynamics under a variety of plausible scenarios. Simulation modelling can only be as credible as our understanding of natural disturbances permits and cannot forego in-depth research on individual disturbance agents. Paleoecological studies are also important, particularly for suggesting the size and direction of the effects of future climate change (Flannigan et al. 2001).*

Gaps in quantifying specific attributes of disturbances.

- Most research has focused on disturbance return intervals; there is little work on other attributes of disturbances, such as extent, severity, and duration, in British Columbia. In some BEC subzones, the relative importance of different disturbance regimes is poorly understood; for example, the relative role of stand-maintaining versus stand-replacing disturbances in some ICH, IDF, or SBPS subzones.

Recommendations:

5. *Use Part 1 of this report to focus research on filling gaps on spatio-temporal dynamics of different disturbance agents in British Columbia. This could include describing patch and remnant size distributions, and remnant composition and structure. Ideally, research should be a combination of fieldwork, gathering empirical data, and simulation modelling to examine the various possible outcomes due to temporal and spatial variability in disturbance attributes, uncertainty, and specific assumptions made in the analysis.*
6. *Define what determines a "predominant disturbance regime" (e.g., stand maintaining may be the predominant regime when intervals of stand-replacing disturbances are twice as long as the lifespan of seral species), and then gather local expertise to determine the predominant disturbance regime in each subzone/variant.*

Gaps in using existing multi-temporal data.

- Many parameters directly related to the occurrence of natural disturbances can be reliably estimated from aerial photography or other remote sensing data. Re-interpretation of old photography (e.g., the 1938 series) to modern standards could help (1) to extend quantitative disturbance analyses further back in time; (2) to potentially resolve some of the issues around pre-harvesting age of stands; (3) to provide a temporal reference more reliable than roll-back modelling for evaluating landscape change; and (4) to cross-check the accuracy and consistency of air photo interpretation.

Recommendation:

7. *Develop standards and initiate a program for conducting, storing, and cataloguing multi-temporal air photo–based forest cover maps. Emphasize estimating attributes relevant to the analysis of natural disturbances (e.g., ecological and spatial descriptors of crown damage, standing dead trees, canopy gaps, and remnant patches).*

Gaps in knowledge about methods-related assumptions to which quantitative estimates of disturbance attributes are most sensitive.

- Part 3 of this report illustrated the sensitivity of estimates of historical disturbance intervals to assumptions tied to the input data. For example, in the Arrow TSA, inaccuracies in age data in the FIP database error were not as influential on the results as assumptions made about the pre-logging age of harvested stands. In this case, research should try to provide data on what stand ages were targeted in the past by logging.
- Another influential factor to clarify is the issue of age-dependent susceptibility to disturbances. To our knowledge, no formal studies in British Columbia have examined how fire and other disturbance agents combine to shape overall susceptibility to disturbance.

Recommendation:

8. *Research disturbance as an iterative process in which a first round of analysis would pinpoint methods-related assumptions that have large leverage on the outcome of the analysis. Uncertainty about sensitive* a priori *assumptions can then be addressed through field studies or archival work to refine further analysis.*

4.3 Recommendations Regarding Data Collection and Maintenance

Gaps in systematic records of natural disturbances in British Columbia.

- The historical records of provincial and federal agencies about fires, insects, and diseases have proven useful in characterizing disturbances in British Columbia. However, these records become less complete and accurate when moving further back in time. For other influential types of disturbances, such as windthrow or mass wasting, records of recent large events exist in the B.C. Ministry of Forests Forest Health Surveys but there are typically no records of severity at the individual stand level in a central forest inventory (Mitchell and Belik 2001).

Recommendation:

9. *Maintain and upgrade historical records of fire and insects. Continue the documentation of large windthrow and flooding events and consider the systematic documentation of windthrow and other stand-level agents at a finer resolution.*

Gaps in FIP database records about pre-harvesting conditions of stands.

- The absence of information about the attributes of forest stands *before* harvesting is one of the most influential factors in determining the level of uncertainty associated with reconstructing the historic variability of stand-replacing disturbances (see Part 3, this report). If reconstruction of historical disturbance frequency from FIP or similar (e.g., Vegetation Resource Inventory [VRI]) data are used more widely in the future—as the current level of interest suggests—the lack of data about stand-age distributions before industrial logging will remain an imposing obstacle to obtaining reliable results, especially as the relative proportion of harvested stands in the landscape increases and evidence about historical forest conditions is further eradicated.

Recommendation:

10. *Retain complete records of pre-harvesting polygon attributes and fill existing gaps through archival information (outside of forest inventory) or field surveys wherever possible. Consider creating new fields that may better reflect date of stand origin.*

Gaps in FIP database records of disturbance-related attributes.

- In our dealings with FIP data from various regions of British Columbia we found that those attributes that could help in estimating aspects of natural disturbances—such as the fields "ACTIVITY_SUB_CD," "DISTURBANCE_PERCENTAGE_CD," and "DISTURBANCE_CD"—are rarely filled in or are "currently not in use." A consistent attention to these attributes during future field surveys and air photo analyses (i.e., during scheduled updates to the FIP or VRI databases) would provide a valuable temporal and spatial record for initial assessments of disturbance activity in all forested areas.

Recommendation:

11. *Collect field and air photo data of evidence of natural disturbances consistently and use all-available fields in the inventory. Consider creating new fields to describe disturbance severity.*

Gaps in FIP database with respect to data accuracy.

- The precise values contained in the FIP database fields give the often-misleading impression of high accuracy. Where audit data are available, statistical error models can be developed (see Part 3, this report; also see B.C. Ministry of Forests 1999) and their parameters added as direct or indirect indicators of data accuracy. Moreover, these models can then be applied in a wide variety of formal analyses that use FIP data as input.

Recommendation:

12. *Use available field data to develop local or regional statistical error models for integration into the FIP or VRI databases as a measure of data accuracy. Incorporate error models into any estimates of past or future landscape dynamics.*

Gaps in collecting and distributing knowledge about natural disturbances.

- Our literature review, along with complementary projects such as Hawkes et al. (1997) and Wong (2001), could provide the foundation for a central database of research about natural disturbances in British Columbia. After having completed some form of peer review, this database should be made available to the interested public as well (perhaps through a Web site) and should be updated regularly.

Recommendation:

13. *Develop and maintain a central database of disturbance-related research and make it available to anyone interested in natural disturbances in British Columbia and elsewhere.*

4.4 Recommendations Regarding Quantitative Methods and Tools

Gaps in applying methods and communicating results effectively.

- Meaningful and defensible research depends on adherence to a method's sampling design, data collection, and data analysis requirements. While we did not try to systematically or critically review the methods presented in the reports and papers available to us, we frequently discussed among ourselves at length because a study lacked in transparency or crucial information about methods and assumptions. We believe that this is because many projects lack a formal peer review.

Recommendations:

14. *Researchers should be familiar with the assumptions and shortcomings of all available methods, as well as with academic discussions about methodological issues (e.g., Finney 1995; Fall 1998; Lertzman et al. 1998; Armstrong 1999; Huggard and Arsenault 1999, 2001; Reed and Johnson 1999; Baker and Ehle 2001).*
15. *Cursory and subjective field reconnaissance—for example, visual inspection of fire scars or substituting dbh for age data—is likely to provide misleading results. Carefully consider sampling standards and protocol, and collect data in a way that allows meaningful analysis.*
16. *Researchers should be encouraged to include a thorough peer review as part of research projects.*

Gaps in methods for quantifying attributes and consequences of stand-maintaining disturbances.

- Stand-maintaining disturbances are more than just temporary reductions in timber volume. Our literature review highlights research that documented the often long-term consequences of small-scale events, whether they are endemic or episodic. Collecting empirical data about the attributes, effects, and interactions of stand-maintaining events involves intensive sampling and is generally highly site-specific. There is an obvious lack of methods for estimating or modelling these attributes from readily available inventory data.

Recommendation:

17. *Develop methods and tools to estimate attributes of stand-maintaining disturbances from data sources other than those that result from intensive fieldwork.*

Gaps in methods and tools for spatial analysis and prediction of disturbance dynamics.

- Most natural disturbances are specific to a particular life stage of a biological host, are associated with site-specific topo-edaphic conditions, or change their attributes (e.g., intensity, rate of spread) depending on where they occur. Therefore, both retrospective research and predictions of future dynamics are meaningful only if topography and adjacency are taken into account (Turner 1989; Cumming 1997; Gavin 2000; Kramer et al. 2001; Morgan 2001; Dorner and Lertzman, in prep.). Recent attempts at incorporating disturbance dynamics into spatial models of forest development show promising results (Fall 1999; Sachs 1999).

Recommendation:

18. *We recommend continuing development of provincial standards and software tools for spatial timber supply analysis.*

4.5 Recommendations Regarding Developing Methods for Incorporating Knowledge on Natural Disturbances into Forest Planning and Management

Gaps in interpreting the historical temporal and spatial variability in disturbance dynamics.

- Most research on natural disturbances spends little effort on interpreting the influence of uncertainty in data quality and assumptions on results.
- Variability in disturbance attributes may be as or more important to understand than the means.

Recommendations:

19. *Choosing a historical reference period should be based on a period with both adequate historical variability and confidence in the data (Landres et al. 1999). Part 3 of this report illustrates that uncertainty in disturbance intervals increases the further one moves back in time. Choosing a historical reference period could be based on some* a priori *acceptable period of uncertainty, such as a threshold based on the inter-quartile range (the box length of boxplots in the third set of figures in each of the summaries in Part 3), although the shorter the reference period is, the less likely it represents the true range of variability for the historical period.*
20. *Design modelling scenarios such that the upper and lower bounds of possible outcomes in disturbance dynamics are characterized. For example, assuming no age dependence in susceptibility to disturbance is a "lower-bound" assumption because it will lead to shorter return intervals than assuming some form of increasing susceptibility with age (see Part 3 for more details).*
21. *Develop a transparent process for incorporating the complex output describing historical disturbance dynamics that result from an analysis such as Part 3 into forest planning and management. This process should be developed with the input from ecologists, analysts, and experts involved in the operational and long-term planning aspects of forest management.*

Gaps in incorporating the spatial and temporal variability of natural disturbances in timber supply analyses.

- Current timber supply analyses in British Columbia, based on growth and yield projections computed with FSSIM (B.C. Ministry of Forests 1997), are primarily non-spatial, and natural disturbances are incorporated by representing them as static rates of loss (i.e., annual "unsalvaged losses"). Initial attempts at developing spatial projections based on "representative" sub-units have proven to be problematic (B. C. Ministry of Forests 1999). However, using fixed rates instead of some form of temporal variability may mask important short- to mid-term consequences of disturbances, such as changing seral stages, spatial adjacency issues, loss of habitat, and species conversion (Morgan 2001). While the random components of stochastic disturbance events cannot be predicted, the expected stochastic effects can be incorporated through Monte Carlo simulation into a spatial form of timber supply analysis.

Recommendations:

22. *Develop procedures for estimating future risk of disturbances (parameterized with field research) to capture age- and species-dependent predisposition of forest stands to disturbances and their variability over time.*
23. *The focus on emulating disturbance rates overlooks the importance of maintaining structure and composition at the stand and landscape levels. We suggest that using historical seral stage distributions may be a more appropriate tool for management than simple disturbance rates.*

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Allowable annual cut (AAC) A target volume of wood to be harvested annually, determined by the Chief Forester informed by a *Timber Supply Review*, which considers ecological and socio-economic implications of different harvest levels.

Area disturbance frequency The inverse of the *mean area disturbance return interval*.

(Mean) area disturbance return interval The average interval between two consecutive disturbances occurring within a given area. The consecutive disturbances used in the calculation need not occur at the same location, only within the general area. Because the number of disturbance events observed in a given area increases with the size of the area, the mean area interval is dependent on the size of the study area: given the same disturbance regime, the bigger the study area, the shorter the mean area interval. Unless every disturbance affects the whole area under consideration, area intervals are shorter than (point) *disturbance return intervals*, and area frequency is higher than the *point disturbance frequency*.

Audit plot data Data collected from ground plots for the primary purpose of verifying *Forest Inventory Planning* (FIP) information.

Biodiversity Guidebook This Forest Practices Code guidebook provides objectives for maintaining biodiversity at both the landscape and stand levels. At the landscape level, guidelines are provided for the maintenance of seral stage distribution, patch size distribution, and landscape connectivity.

Cohort of trees A group of trees that have established at approximately the same date and location.

Dendrochronology The study of patterns in tree rings to date events or determine forest dynamics; for example, dating of patterns of suppression and release in growth can indicate insect outbreaks. Dendrochronological analyses differ from simple counting—they use master chronologies (a chronology of ring patterns from climatically responsive trees, such as those on ridges) to match patterns in tree rings to known dates (crossdating). This method avoids misdating due to missing or false rings.

Descriptive vs. process-based models A *descriptive model* identifies important observational variables for a particular system, as well as the strength of correlation between different observed variables. A *process-based model* tries to model the underlying processes and causal relationships responsible for systems dynamics and current system state.

Disturbance intensity The energy emitted by disturbances at the time of the event. For example, fire intensity is measured by the energy emitted per unit length of fire front.

Disturbance regime Regimes typically describe the frequency, size, intensity, severity, and seasonality of disturbances. *Disturbance regimes* can differ between different locations due to the influence of topography, regional climate, or forest structure.

(Mean) disturbance return interval The average time between consecutive disturbances at a location.

Disturbance severity Linked to disturbance intensity; it is the effect of disturbances on the landscape (e.g., effect on patch distribution) or in a stand (e.g., degree of mortality, effect on stand structure). Crown fires are typically high severity and surface fires are low severity.

Fire cycle See (mean) *disturbance return interval*, *natural fire rotation*.

Fire scar A cat-face scar located at the base of a tree where a fire burned part of the cambium but did not kill the tree. A finely sanded cross-section of the scar area can be used to date the fire.

Forest Inventory Planning (FIP) database Provincial forest inventory database, containing a wide range of stand attributes and some information on stand history. Most of the information in the database is obtained by interpretation of aerial photography.

Historical range of variability (HRV) The temporal and spatial distribution of forest pattern and/or processes in the past, typically before European settlement of North America.

Homogeneity in space Similarity in forest attributes or processes between different locations in a stand or landscape.

Homogeneity in time Similarity in forest attributes or processes through time.

Homogeneous spread of disturbance Disturbances that spread at equal rates in all directions.

Landscape-level biodiversity See *Biodiversity Guidebook* for description.

LANDSUM A spatially explicit model used to determine the range of variability in landscape pattern resulting from a variety of processes, such as insect outbreaks, logging, and fire (Keane et al. 1997).

Mark-recapture statistics Statistical analysis that allows inferences about the total population size based on the number of times previously marked individuals are recaptured. In the present context, the population in question is the population of disturbance events, and the "traps" used to capture and recapture individuals are trees recording disturbance events.

Maximum likelihood estimate (MLE) Given a statistical process model, the maximum likelihood estimate of the model parameters is the set of parameters that agrees most closely with the observed data.

Monte Carlo simulation Repeated simulation of a stochastic model to obtain the range of expected values or outcomes created by the model.

Natural fire rotation Also known as *fire cycle*. A popular measure of fire frequency in the fires history literature, formally defined as the time it takes for the equivalent of the study area to burn. Assuming the disturbance regime is homogeneous across the study area, this is equivalent to the *(mean) disturbance return interval*.

Natural rotation interval See *disturbance return interval*.

Negative exponential distribution Describes the expected distribution of disturbance intervals if disturbance is assumed to be a stationary Poisson process. See also *Poisson process, Weibull distribution*.

Non-timber values Values derived from forests that are not related to wood extraction, including wildlife habitat, recreation, visual quality, or harvesting of mushrooms.

Operational adjustment factor Currently used in timber supply analysis to adjust for operational conditions that lead to lower yields than predicted by growth and yield models. OAF1 reductions are constant across all stand ages (e.g., typically stocking gaps or unmapped inoperable areas), whereas OAF2 reflect the probability that reductions in volume will increase as stands age (e.g., due to abiotic and biotic stand-maintaining disturbances). Currently, many timber supply reviews use the provincial default for OAF2 of 5% to incorporate losses due to low- to mixed-severity disturbances.

Oversampling Involves sampling in one part of the study area at a finer grain relative to the larger sampling strategy. Oversampling can be used to determine the effect of the sampling resolution on calculations of disturbance parameters.

Parametric model A mathematical model described by one or more key parameters, which determine model behaviour. See also *Poisson process* as an example of a parametric process model.

Period of reliability Period over which a dataset is considered to provide reliable information of consistent quality.

Point disturbance frequency The inverse of the average number of years elapsed between consecutive disturbances at a point in the landscape. If susceptibility to disturbance is assumed to be the same everywhere in the landscape, this is equivalent to the proportion of the study area disturbed per year. Also used to refer to the key parameter in mathematical models of disturbance regime. See also *disturbance regime, (mean) disturbance return interval, (mean) area disturbance return interval, Poisson process*.

Poisson process Statistical model of event occurrence over time and/or space. Its main assumptions are that events occur at random, independent of each other, and that the process rate remains stationary for the time period and/or spatial unit under consideration. For example, consider time or space divided up into discrete units (e.g., years, raster cells). Then the distribution of the number of events occurring in each unit is described by a Poisson distribution. The parameter of the Poisson distribution, λ, gives the average, or expected number of events occurring in a unit (i.e., the event frequency). See also *stationary in time.*

Provincial Fire Atlas Collection of maps with approximate origin and final perimeter of historical fire events.

Range of natural variability (RNV) Range of dynamics or conditions naturally occurring throughout the landscape or ecosystem. The closely related range of historical variability refers to the range of conditions or dynamics historically present in a given landscape or ecosystem. See also *historical range of variability.*

Recorder trees Trees that, because of their physical attributes or recent history, would be assumed to show a record of a disturbance event if such an event occurred in a given year at the site.

Remote sensing data Data obtained by airborne or satellite sensors.

Rollback Method A method for reconstructing historical age-class distributions.

SELES Spatially Explicit Landscape Event Simulator. A high-level programming language and development environment for building stochastic simulations of landscape dynamics (Fall and Fall 2001). See also *spatially explicit stochastic simulation model.*

Seral stage Developmental stage of a forest stand. Typically, stand age is used as a proxy to indicate seral stage, although age-based definitions of seral stage are not necessarily meaningful for all forest types.

Seral stage distribution The relative proportion of forest in different seral stages throughout the landscape.

Spatial autocorrelation An important property of spatial analysis and sampling design. For example, consider a landscape that has been sampled by a regular grid of sampling plots. Spatial autocorrelation indicates to what degree nearby plots tend to have more similar cover attributes than plots further apart. Spatial autocorrelation can significantly influence the validity of statistical tests that compare sample distributions.

Spatially explicit stochastic simulation A model that simulates the occurrence of stochastic processes across space. See also *stochastic process.*

Standing age distribution The relative proportion of forest area in different age classes.

Stand-maintaining disturbances Disturbances that leave a large proportion of the canopy intact.

Stand-replacing disturbances Disturbances that kill most of the canopy trees and thus create appropriate conditions for the establishment of a new *cohort* of trees.

Stationary in time A process is considered stationary in time if its main characteristics, such as process rate, do not change over time. See also *homogeneity in time, poisson process.*

Statistical power Formally, the probability of rejecting the null hypothesis when a treatment effect of a given size is present. Thus, power is a measure of the ability of a given experimental setup to detect an existing effect. See also *statistical significance.*

Statistical significance Formally, the probability of incorrectly rejecting the null hypothesis. Statistical significance is a measure of the confidence that an observed difference between treatments is due to treatment effects, rather than extraneous random variation among samples. See also *statistical power.*

Stochastic process A process whose behaviour has random aspects. See also *Poisson process.*

Susceptibility to disturbance The probability that a stand with a given set of characteristics will be disturbed. In this report, we use the term susceptibility in a relative sense to answer the question "Given that there is a disturbance somewhere in the landscape, which stands are the most likely ones to be affected?" Thus, susceptibility is expressed as a ratio (e.g., stands 80 years or older are two times more likely to be disturbed than younger stands).

Timber Supply Review Process regularly undertaken by the Ministry of Forests to estimate currently available volume of harvestable timber and forecast future supplies. Used as a key input for AAC determination. See also *allowable annual cut.*

Time since disturbance Time elapsed since the last disturbance event. In areas dominated by stand-replacing disturbance regimes, stand age is often used as a proxy for the time elapsed since the stand was last disturbed.

Uncensored record A data record that has not been subject to systematic removal of sample values in a particular range. Censoring may occur either by natural processes (e.g., when a high-severity disturbance removes evidence of previous disturbances), or it may be a result of sampling strategy, data preparation, or forest management activities. See also *period of reliability.*

Weibull distribution A statistical distribution function that describes the expected shape of the disturbance interval distribution if susceptibility to disturbance varies with stand age. The reverse cumulative form of the Weibull distribution is given by $e^{-(x/\beta)^{\alpha}}$ (i.e., for the special case of $\alpha = 1$ the Weibull distribution reduces to a negative exponential distribution). See also *negative exponential function.*